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# A STUDY OF FLOW CONDITIONS ARISING IN HORIZONTAL COARSE SLURRY SHORT DISTANCE PIPELINING PRACTICE PHASE 1: SAND-SLURRY TESTS IN A 250 mm PIPELINE

FINAL
~~Interim~~ Report

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R.G. Gillies, W.H.W. Husband
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99 pp

Publication R-833-2-C-85

September, 1985

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R.G. Gillies, W.H.W. Husband,
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for

C.A. Shook Consulting Ltd.

Work on this project was conducted under the auspices
of the Canada Centre for Mineral and Energy Technology,
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## SUMMARY

With growing interest in pipeline transportation of slurries of coarse coal, a reliable method is required to extend available data. The Canada Centre for Mineral and Energy Technology, Department of Energy, Mines and Resources Canada has provided funding to generate the data necessary to develop a suitable predictive method. The experimental portion of the program was conducted by Saskatchewan Research Council under sub-contract to C.A. Shook Consulting Limited.

Tests were conducted in a 250 mm diameter (nominal) horizontal pipeline loop using coarse coal-in water slurries and coarse sand-in-water slurries. Pressure gradients, concentration profiles, particle velocity distributions and delivered mixture concentrations were determined as functions of slurry flowrate and pipeline in-situ concentration.

The results of the coarse coal-in-water slurry tests are reported under separate cover (Phase II: Coal-slurry tests in a 250 mm pipeline). The sand slurry test results are presented in this report. The results of the pipeline loop tests were applied to improve the two-layer model for flow of slurries in pipelines. The model development work is also presented here.

A probe for measuring point values of solids concentration has been developed at the University of Saskatchewan. The probe was tested in a 495 mm diameter pipeline and the results are included in this report. The test results verified the excellent performance of the probe.

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# 1. INTRODUCTION

In recent years significant advances have been made in techniques for measuring important parameters for the flow of slurries in pipelines. Measurement of local or point velocities and solids concentrations are now possible. In the past, only spacially-averaged values of velocity and solids concentration could be measured.

The first approach to solving slurry flow problems was to use spacially-averaged velocity and solids concentration measurements along with pressure gradients, pipe diameter, etc., in dimensional analyses devised to extend the useful range of the available experimental data. A lack of suitable test results restricted the validity of the method. The method did not provide insight into the flow structure.

The more recent approach has been to develop mathematical models for the slurry flows based upon rational consideration of the mechanisms of energy dissipation in the pipeline. One such approach is the two-layer model originally proposed by Wilson and co-workers (Reference 1). The model consists of coupled force balance and mass balance relationships for two segmented regions. The model's assumed flow regime differs significantly from experimentally determined velocity and concentration profiles. However, the two-layer model has been shown to be very

successful for coarse-particle flows at high concentrations by independent experimental investigations such as that of Televantos et al. (Reference 2). Further confirmation has been given by the thorough literature review funded by the USDOE and conducted by Eyler et al. at Battelle NW Laboratories (Reference 3).

One of the essential features of the model is the role played by particles which are too large and/or too dense to be suspended by fluid lift forces. These are the so-called contact load particles, which produce increased frictional energy consumption during pipeline flow.

The model has not been as successful for fine-particle slurries or for the transition category between coarse-particle and fine-particle slurries. This failure is due to inadequate predictions of the contact load/suspended load ratio in the tentative expressions proposed by Wilson (Reference 4). Further improvements were difficult because there was a dearth of suitable experimental data in the open literature for the transition category. This region corresponds to particles with diameters between 0.5 and 5 mm. Many coarse Canadian coals have mean diameters in this region. Some oil sand deposits being mined at present contain sand particles of this size range.

The more elaborate Roco-Shook model (Reference 5) is based on integration of the differential momentum equations and

predicts concentrations and velocities as continuous functions of position. However, because of the complexity of two-phase flow systems, all numerical solutions must contain some intuitive or empirical components. At its present state of development, the Roco-Shook model requires "fine tuning" of these components to give reasonable headloss predictions for various slurry types. The complexity of the model makes the tuning process difficult. The experimental data generated in this study will be useful for improving the Roco-Shook model, as well as the two-layer model. However, modification of the Roco-Shook model is beyond the scope of the present study.

# 2. EQUIPMENT AND PROCEDURES

## 2.1 Test loop

The pipelining tests were carried out in a 250 mm diameter (nomimal) pipeline loop at the Saskatchewan Research Council (SRC) Slurry Pipeline Development Centre. The loop is shown schematically in Figure 1. A differential pressure transducer was used to measure headlosses over a 29 m long horizontal test section. The inside diameter of the test section was 263 mm. The test section was originally coated internally with epoxy to provide a constant (and low) pipe roughness factor. However, the epoxy coating had been worn away from the lower third of the test section, exposing the carbon steel pipe. Frequent clear water headloss versus velocity measurements were necessary during the test program to obtain accurate estimates of the pipe roughness during each slurry test.

At the start of the program a Linatex rubber lined centrifugal pump with a 300 mm inlet and a 250 mm discharge was used to circulate the slurries. During the test program, the rubber liner separated from the pump impeller. An attempt to replace the liner proved unsuccessful. A new Warman metal lined pump with a 250 mm inlet and a 200 mm discharge was purchased to complete the program. The new pump, although of smaller physical dimensions than the old

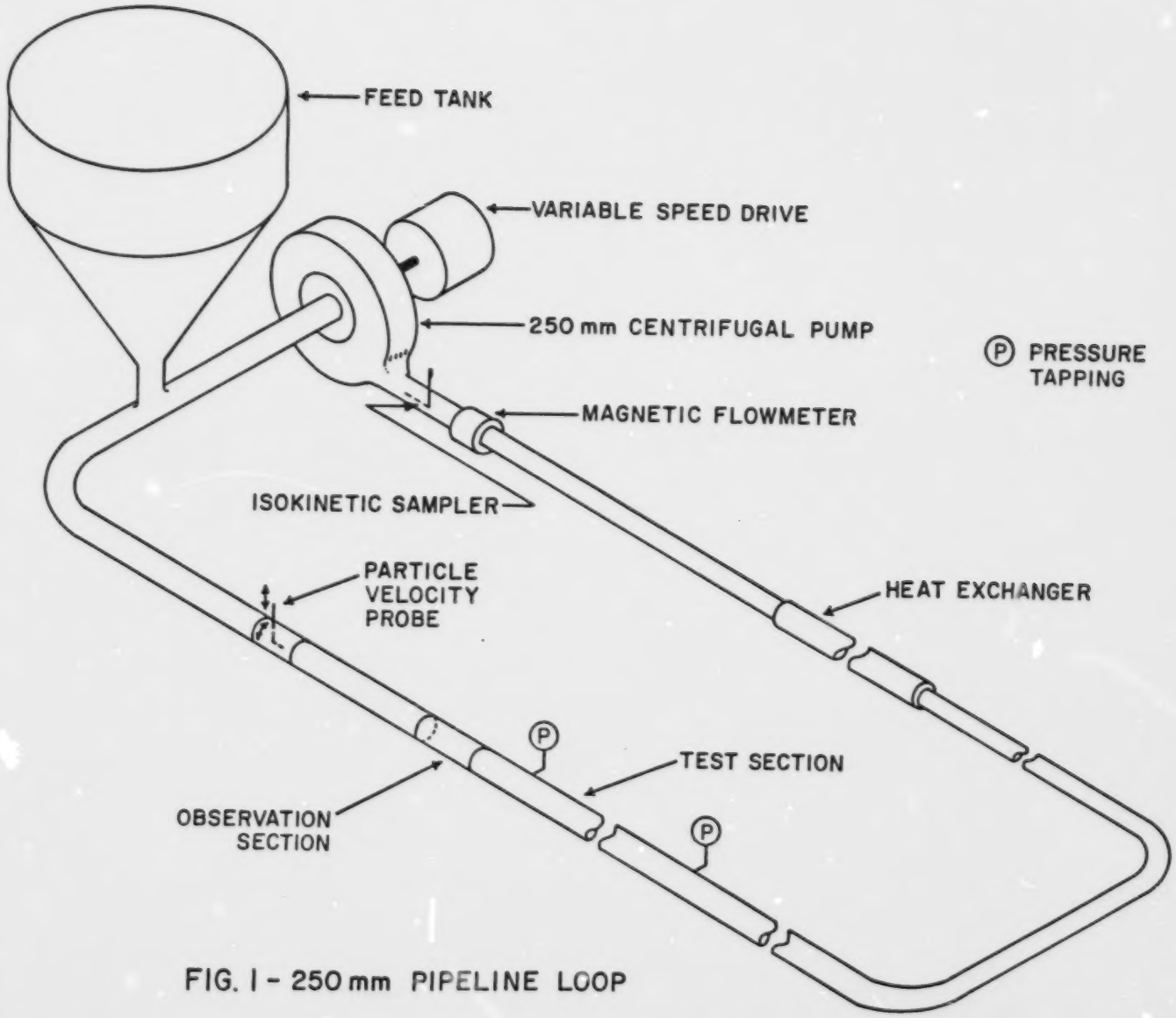



FIG. 1 - 250 mm PIPELINE LOOP

pump, has a higher throughput and made it possible to extend the range of test conditions for the program.

A 190 kW electric motor was used to power the pump. A variable speed fluid drive provided flow control. The slurry flowrate was measured using a magnetic flowmeter.

A chilled ethylene glycol-water mixture was circulated through the annulus of a pipe-over-pipe heat exchanger to maintain a constant slurry temperature. Temperature was controlled within 1°C.

The slurry flow regime was determined by visual inspection through a transparent acrylic section of pipe and with a Snamprogetti detection probe (Reference 6). The probe was flush-mounted on the pipe wall. The probe detects fluctuations in slurry electric resistance which result from the "macroturbulent" particle concentration fluctuations in the flow. These fluctuations increase in amplitude as the slurry velocity decreases and then disappear entirely if the probe becomes covered with a stationary deposit of particles.

A Hewlett-Packard 9825A computer and a NEFF 620 multiplexer system measured and recorded all sensor readings. Instrument calibrations were performed prior to the sand slurry tests. Pressure transducers were calibrated using U-

tube manometers. The magnetic flowmeter was calibrated against an orifice plate using water.

Each slurry test consisted of the following steps:

1. The pipeline loop was filled with water.
2. A pre-determined amount of sand was placed in the pipeline through the feed tank. The pipeline was operated at a flow velocity of some 3 to 4 m/s during the addition of solids.
3. Headloss versus flowrate measurements were made starting at the highest flowrate. The flowrate was reduced step-wise until a stationary deposit was observed.
4. Samples for particle size analysis were removed at the pump discharge as soon as the headloss determinations were completed.
5. The concentration profiles were determined at two velocities using a traversing chord-averaging gamma ray gauge. At the same time, particle velocities were determined using an L-shaped probe.

The solids concentration was increased by adding solids to the previously tested slurry. The measurements described above were then repeated for the higher density slurry.

## 2.2 Sampling

Samples were isokinetically withdrawn from the pump discharge section of the test loop to determine the particle size distribution of the solids contained in the mixtures

delivered by the pipeline. It is assumed that the solids are uniformly distributed over the cross-section of the pipe near the discharge of the pump. A 40 mm diameter sampler tube (Figure 2) was used to isokinetically withdraw the sand slurry samples. The pipeline was operated at 4 m/s during sampling.

"Head" samples were obtained by grabbing portions of the solids as they were added to the loop. Head samples were analyzed to obtain the initial pipeline in-situ solids particle size distribution.

2.3 Concentration measurement

Since the pipeline test loop was horizontal and recirculating, the in-situ solids concentration was independent of slurry velocity. A traversing gamma ray gauge was used to measure in-situ solids volume fractions in the 263 mm diameter test section. The gauge is shown schematically in Figure 3. Chord-average values of in-situ solids concentration were determined using a Cs-137 source and an Ortec detection system. The beam was collimated to a height of 6 mm and was traversed mechanically between measuring locations. Absorption coefficients were determined in separate calibration tests. The average in-situ solids fraction was determined by integrating the local solids fractions over the pipe cross-section.

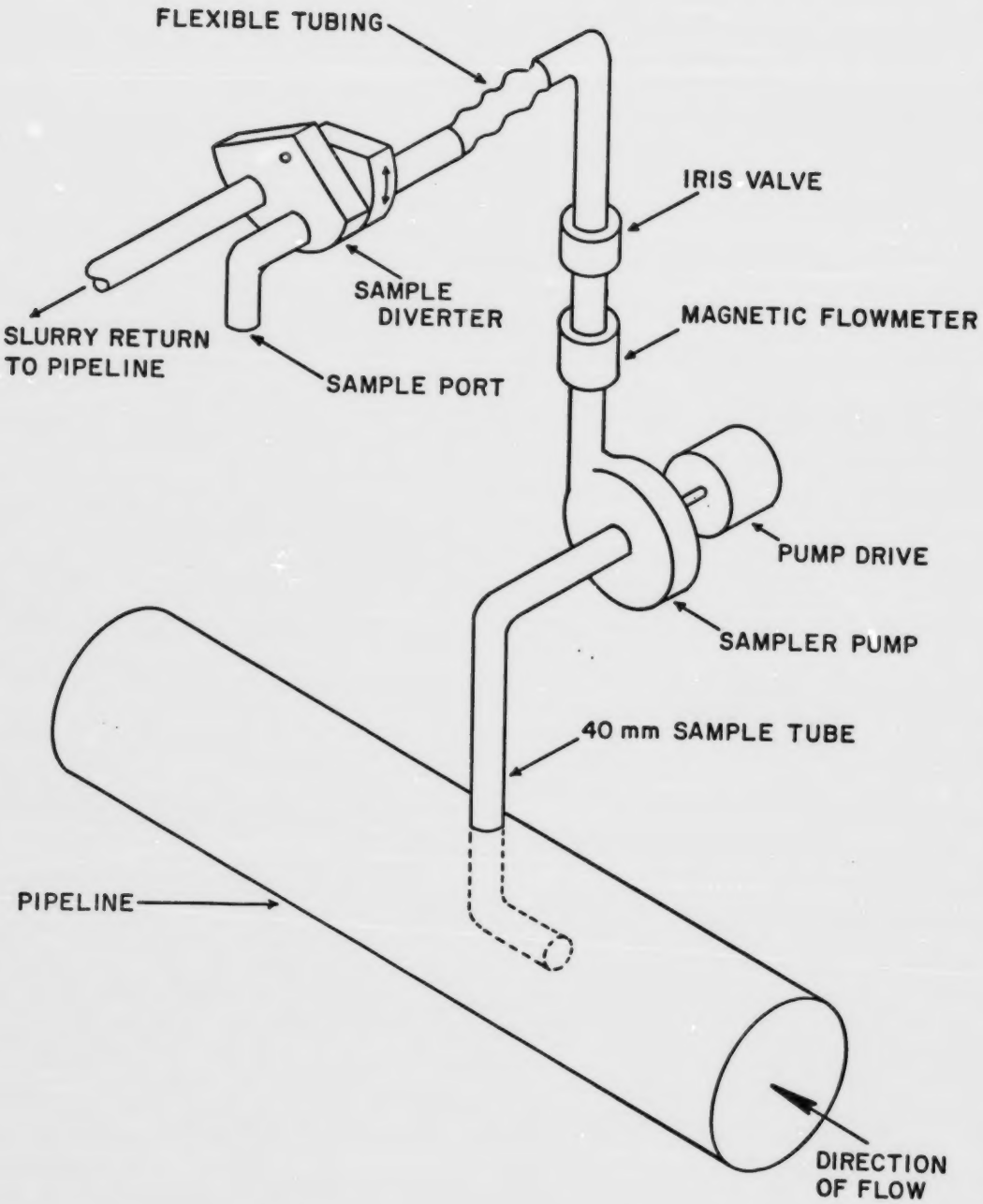



FIG. 2 - ISOKINETIC SAMPLER

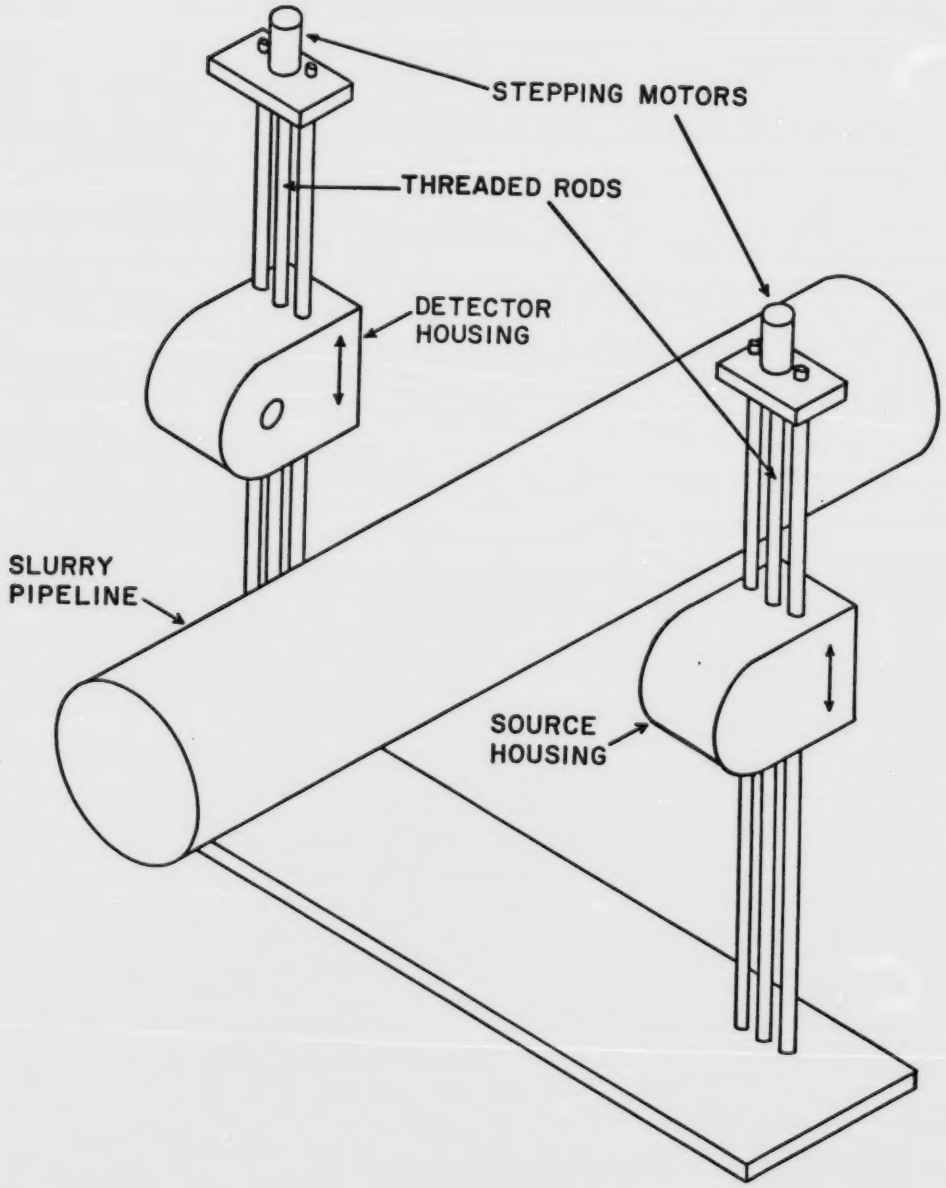


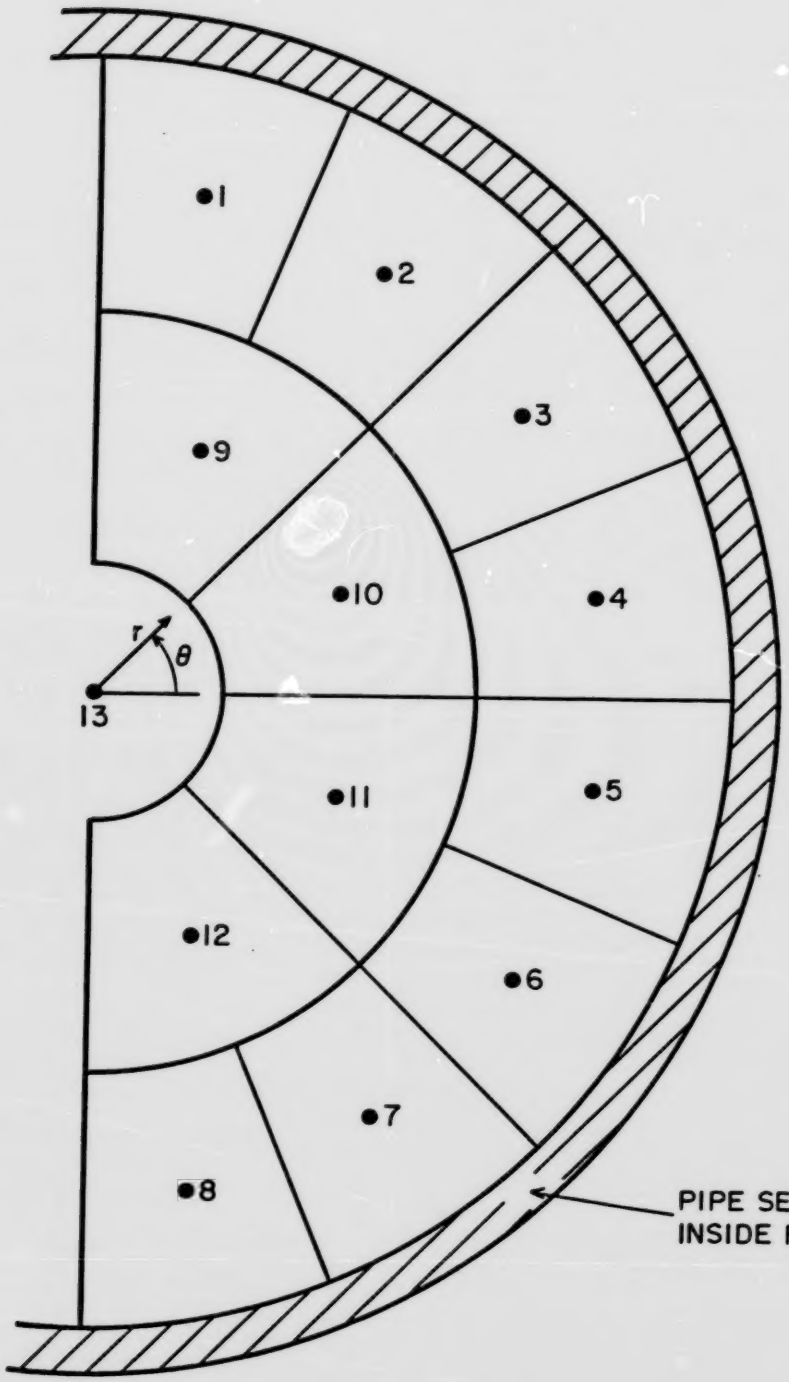

FIG. 3 - TRAVERSING GAMMA RAY GAUGE

$$C_r = \sum_{j=1}^{n} c_j L_j \Big/ \sum_{j=1}^{n} L_j$$

where $C_r$ and $c_j$ are the average and local volume fractions and $L_j$ is the chord length at vertical position j. The measurements were made at ten equally spaced vertical positions.

Delivered solids concentration cannot be measured directly at the SRC facility. It is necessary to calculate the delivered concentration by integrating the product of local concentration measurements (gamma ray gauge results) and local particle velocity measurements. Particle velocity profiles were determined using a probe developed at the University of Saskatchewan Department of Chemical Engineering. Appendix G gives a brief description of the probe. More detailed descriptions are given in References 7 and 8. The probe was located in a pipe section with an inside diameter of 254.5 mm. The pipe section could be rotated to allow sampling at any position. Figure 4 shows the locations of the sampling points used in the present study. The average particle velocity may be determined by assuming that the flow is symmetrical about the vertical axis of the pipe.

$$V_p = \left( 2 \sum_{j=1}^{12} v_j + v_{13} \right) \Big/ 25$$




| POSITION | θ | r/R |
|---|---|---|
| 1 | 78.75° | 0.8 |
| 2 | 56.25° | 0.8 |
| 3 | 33.75° | 0.8 |
| 4 | 11.25° | 0.8 |
| 5 | -11.25° | 0.8 |
| 6 | -33.75° | 0.8 |
| 7 | -56.25° | 0.8 |
| 8 | -78.75° | 0.8 |
| 9 | 67.50° | 0.4 |
| 10 | 22.50° | 0.4 |
| 11 | -22.50° | 0.4 |
| 12 | -67.50° | 0.4 |
| 13 | — | 0.0 |

Fig. 4 - Sampling Positions for Particle Velocity Measurements

where $v_j$ is the particle velocity at location j.

The delivered solids volume fractions are then computed from the results of the particle velocity determinations and the concentration profile determinations.

$$C_{vd} = \left( 2 \sum_{j=1}^{12} c_j v_j + c_{13} v_{13} \right) / 25 V_p$$

where $c_j$ is the solids volume fraction at location j. Linear interpolation of gamma ray gauge data is used to obtain values for $c_j$. It is assumed that the solids concentration is independent of horizontal position in the pipe.

2.4 Solids property determinations

Particle size distributions were determined by sieving. Samples were wet screened using a sieve with 0.074 mm (200 mesh) openings to remove the fines portion. The material passing through the 0.074 mm sieve was collected and dried to determine the weight of the fines. The plus 0.074 mm portion was dried and screened using a series of Tyler sieves and a Ro-tap shaker.

Pycnometers were used to determine the density of the sand samples.

Particle drag coefficients were determined from measurements of the terminal settling velocity, $V_t$ of individual solids

particles in a column of water. The drag coefficient is calculated as follows:

$$C_D = 4\ g\ d\ (\rho_s - \rho_f) / 3\ \rho_f\ V_t^2$$

The drag coefficient is normally reported as a function of the particle Reynolds Number, $d\ \rho_f\ V_t / \mu_f$.

## 2.5 Viscosity determinations

The carrier viscosity was monitored using a Brookfield concentric cylinder viscometer. The minus 0.074 mm fraction of the slurry was considered to be the carrier for the viscosity tests. The slurry sample was withdrawn from the pipeline through the centre stream sampler. The plus 0.074 mm fraction was removed by screening. The water and the minus 0.074 mm fines were transferred to the viscometer and tested as soon as possible to avoid significant settling prior to the test.

The behavior of a slurry in a pipeline is known to be strongly dependent on the carrier fluid viscosity. An increase in carrier viscosity may result in a reduced headloss for a segregated slurry since the carrier's ability to suspended particles is increased. It was planned to systematically study the carrier viscosity effects by adding bentonite clay to the slurries. However, the clay addition produced complex rheological behavior. The carrier exhibited shear history dependent properties. To avoid complicating the model analysis unnecessarily, a more

straight forward method of varying the carrier viscosity was required. As an alternative to adding clay, the carrier viscosity was changed by increasing the temperature of the slurry from the normal 15°C to 40°C.

Runs were also performed with clay added. However, the rheological properties of the clay-containing carrier were not quantified and the results were not used in the model development.

## 2.6 Kinematic friction

For slurries of coarse particles, headlosses exceed those of the clear fluid by an amount which depends, according to theoretical explanations, on the coefficient of friction between particles and pipe. In his description of the particle-wall friction process, Wilson (Reference 9) suggested that a tilting tube could be used to determine the coefficient without flow experiments. More recently, Eyler (Reference 10) has constructed and used an apparatus based upon the the tilting tube principle. Eyler's design was closely followed in an apparatus constructed at SRC. Using the apparatus, it is possible to determine static and sliding friction coefficients for particles submerged in water. Friction coefficients were determined using both carbon steel and epoxy coated pipe materials.

# 3. RESULTS

## 3.1 Experimental

A total of 28 runs were performed in the 250 mm pipeline loop. The results for each run are tabulated in Appendix A. The runs have been grouped into five test series. Table 1 summarizes the conditions for each series.

Figures 5 and 6 show the initial solids size distributions for each series of slurry tests. The plotted distributions represent the initial in-situ particle size since head samples were used. The solids mean size did not change significantly during the tests. However, as shown by the pump discharge sample size distributions (Appendix A), re-circulation in the test loop generated some fines. Fines generation was greatest for slurries containing very coarse solids. Unfortunately, pump discharge samples were obtained incorrectly for the 2x6 mm gravel tests (Series 852507). As a result, the amount of fines could not be quantified.

Figures 7 to 11 show slurry headloss as a function of solids concentration and slurry velocity. A stationary bed exists at the lowest velocity point for each slurry concentration. Generally, the measured headloss decreases with decreasing velocity and then increases at the stationary deposit point. The reason for this increased headloss is not clear. Unlike a once through system, the solids concentration in the test

Table 1. Summary of Test Conditions

| Run Number | Type of Slurry | Solids Vol. Fraction | Temperature (°C) |
|---|---|---|---|
| 8525030 | Water Run | 0.00 | 15 |
| 8525031 | 0.3x1.0 mm Silica Sand | 0.15 | 15 |
| 8525032 | 0.3x1.0 mm Silica Sand | 0.25 | 15 |
| 8525033 | 0.3x1.0 mm Silica Sand | 0.30 | 15 |
| 8525034 | 0.3x1.0 mm Silica Sand +0.5% Clay | 0.31 | 15 |
| 8525035 | 0.3x1.0 mm Silica Sand | 0.30 | 40 |
| 8525040 | Water Run | 0.00 | 15 |
| 8525041 | 0x1 mm Silica Sand | 0.16 | 15 |
| 8525042 | 0x1 mm Silica Sand | 0.25 | 15 |
| 8525043 | 0x1 mm Silica Sand | 0.34 | 15 |
| 8525044 | 0x1 mm Silica Sand +0.5% Clay | 0.34 | 15 |
| 8525045 | 0x1 mm Silica Sand | 0.34 | 40 |
| 8525050 | Water Run | 0.00 | 15 |
| 8525051 | 0x6 mm Silica Sand | 0.15 | 15 |
| 8525052 | 0x6 mm Silica Sand | 0.25 | 15 |
| 8525053 | 0x6 mm Silica Sand | 0.35 | 15 |
| 8525054 | 0x6 mm Silica Sand | 0.35 | 40 |
| 8525055 | 0x6 mm Silica Sand +0.5% Clay | 0.35 | 15 |
| 8525060 | Water Run | 0.00 | 15 |
| 8525061 | 2x6 mm + 0.1x0.3 mm Silica Sand | 0.15 | 15 |
| 8525062 | 2x6 mm + 0.1x0.3 mm Silica Sand | 0.25 | 15 |
| 8525063 | 2x6 mm + 0.1x0.3 mm Silica Sand | 0.35 | 15 |
| 8525064 | 2x6 mm + 0.1x0.3 mm Silica Sand | 0.35 | 40 |
| 8525070 | Water Run | 0.00 | 15 |
| 8525071 | 2x6 mm Silica Sand | 0.13 | 15 |
| 8525072 | 2x6 mm Silica Sand | 0.22 | 15 |
| 8525073 | 2x6 mm Silica Sand | 0.22 | 40 |
| 8525074 | 2x6 mm Silica Sand +0.5% Clay | 0.23 | 15 |

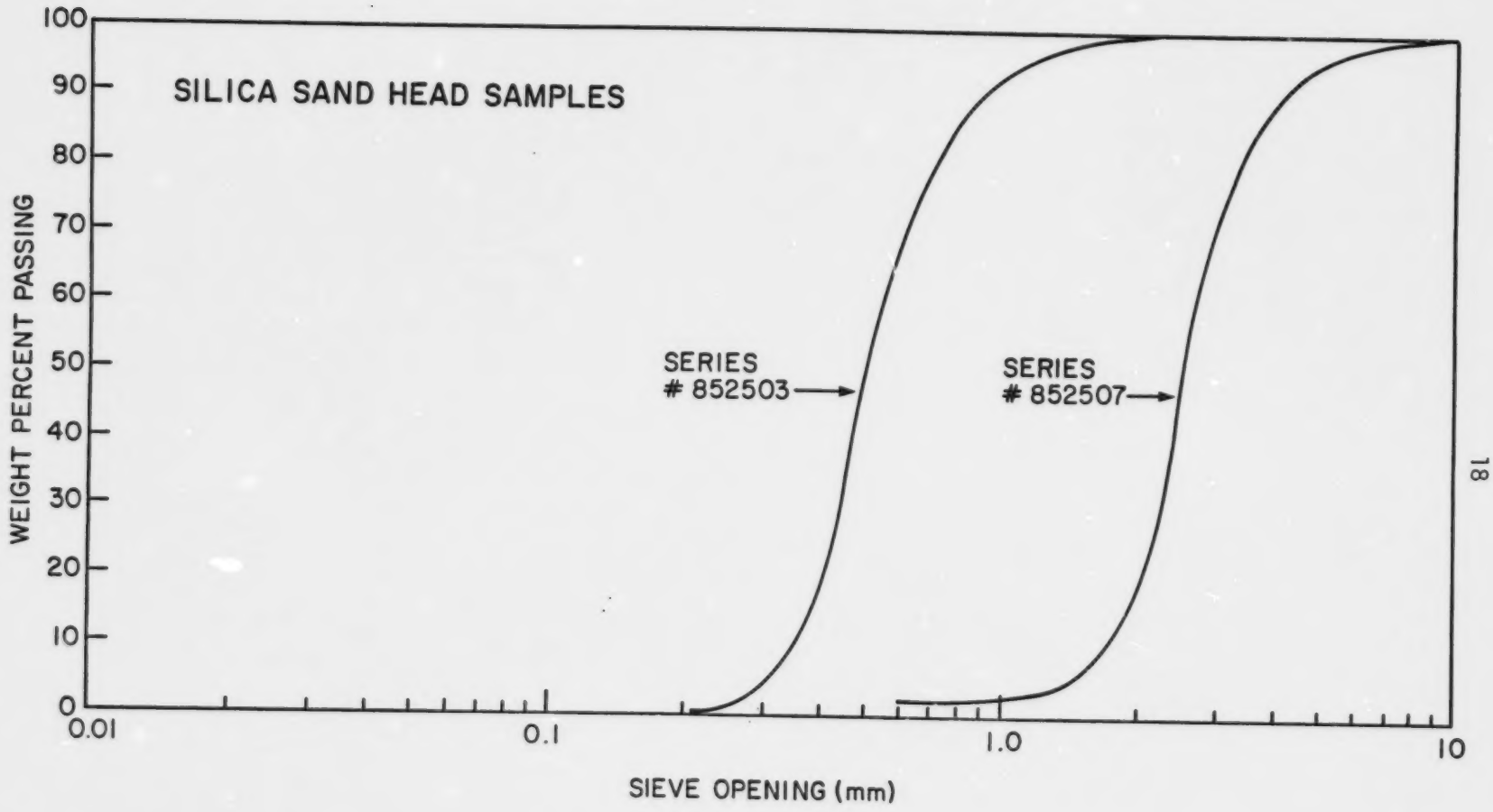



Figure 5. Size distributions for narrowly sized sands.

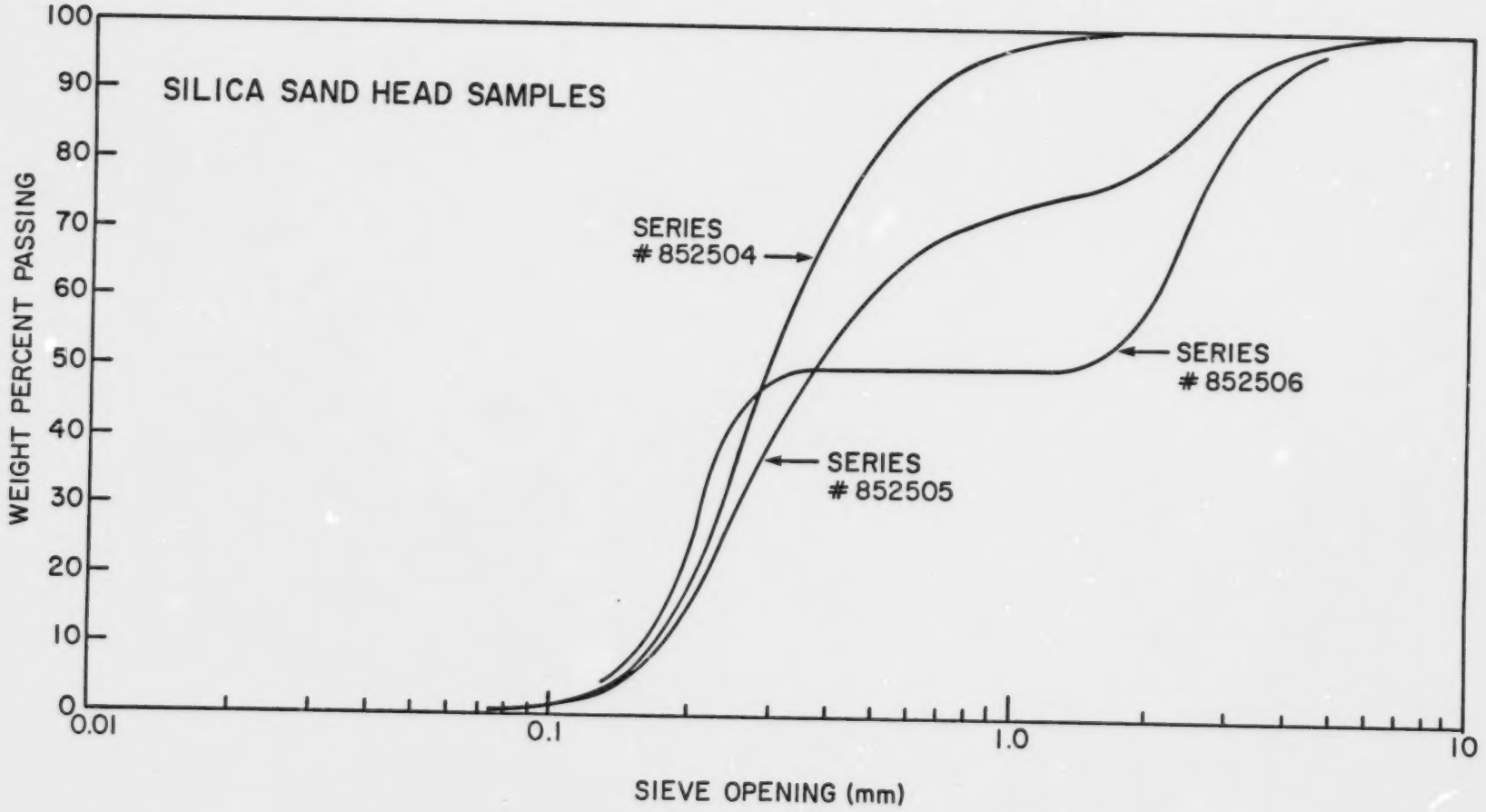



Figure 6. Size distributions for broadly sized sands.

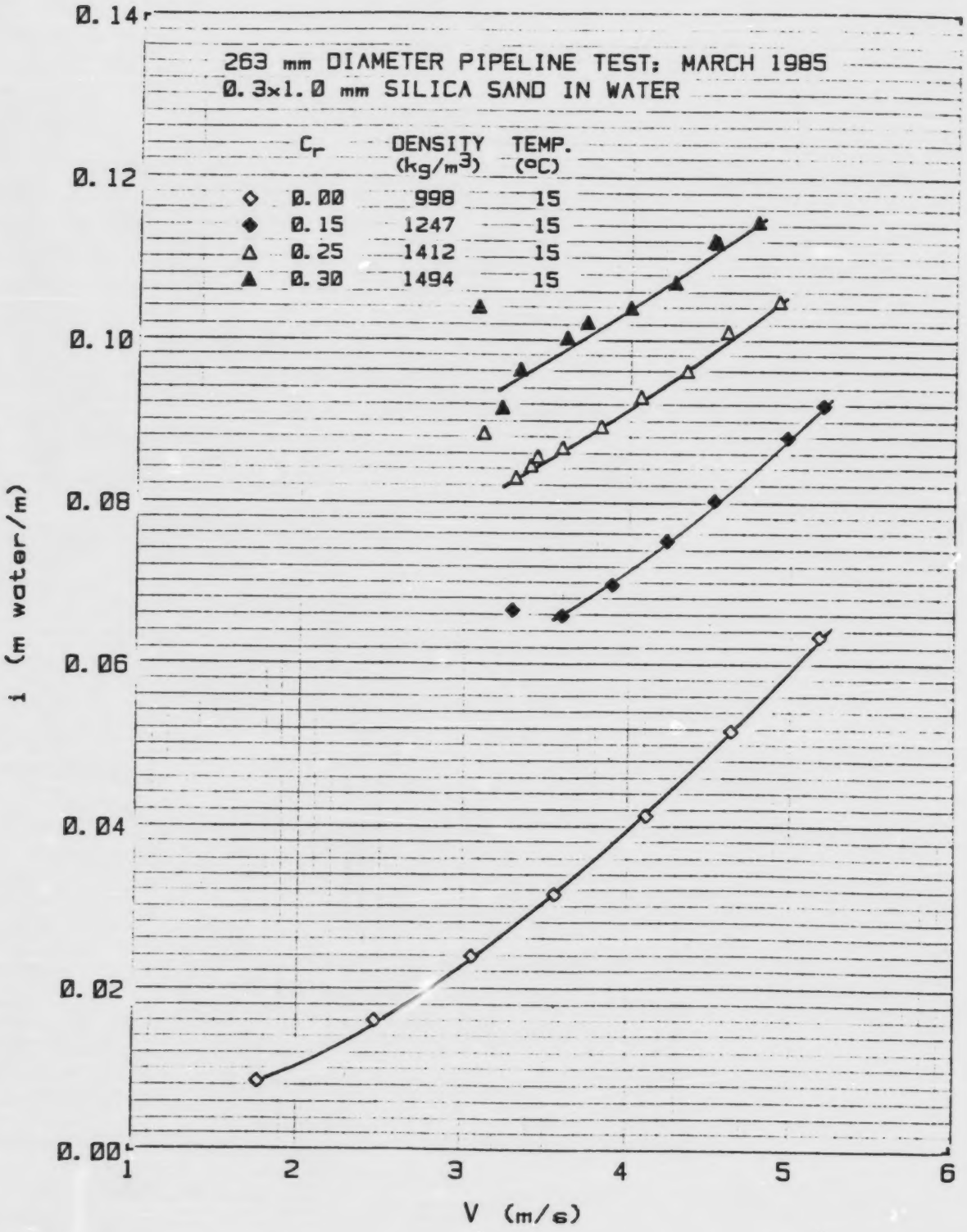



Figure 7. Headloss vs Velocity for Test Series #852503

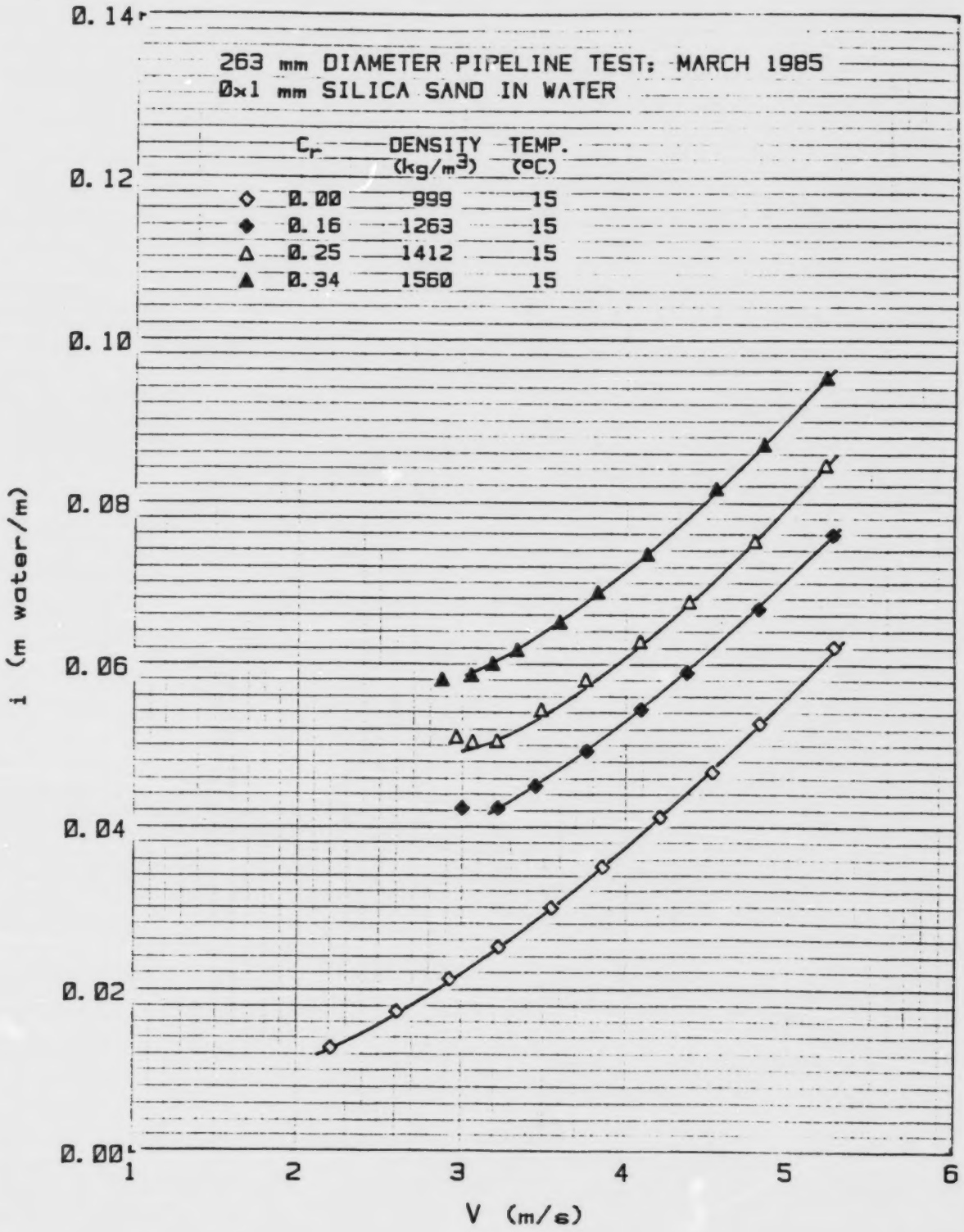



Figure 8. Headloss vs Velocity for Test Series #852504

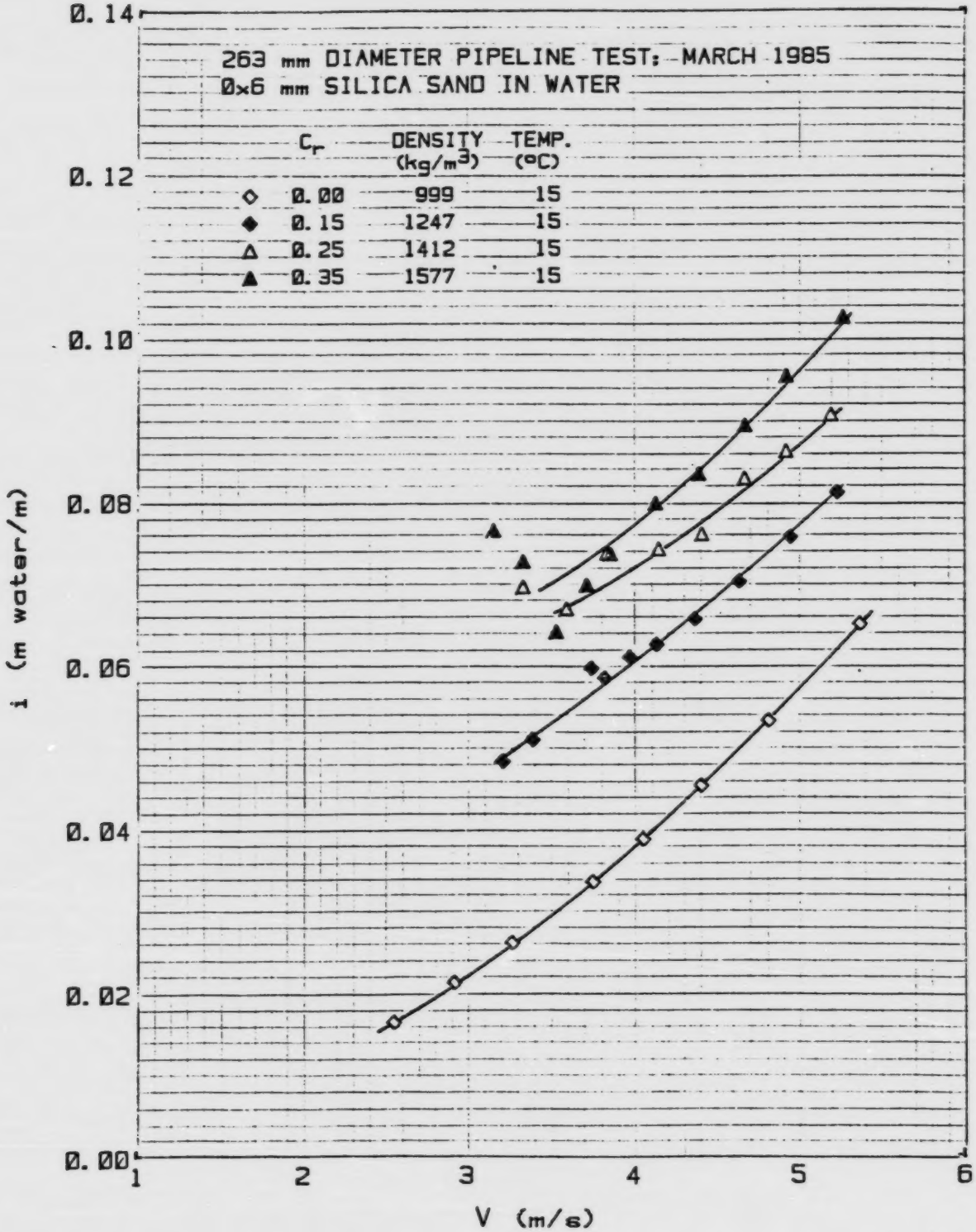



Figure 9. Headloss vs Velocity for Test Series #852505

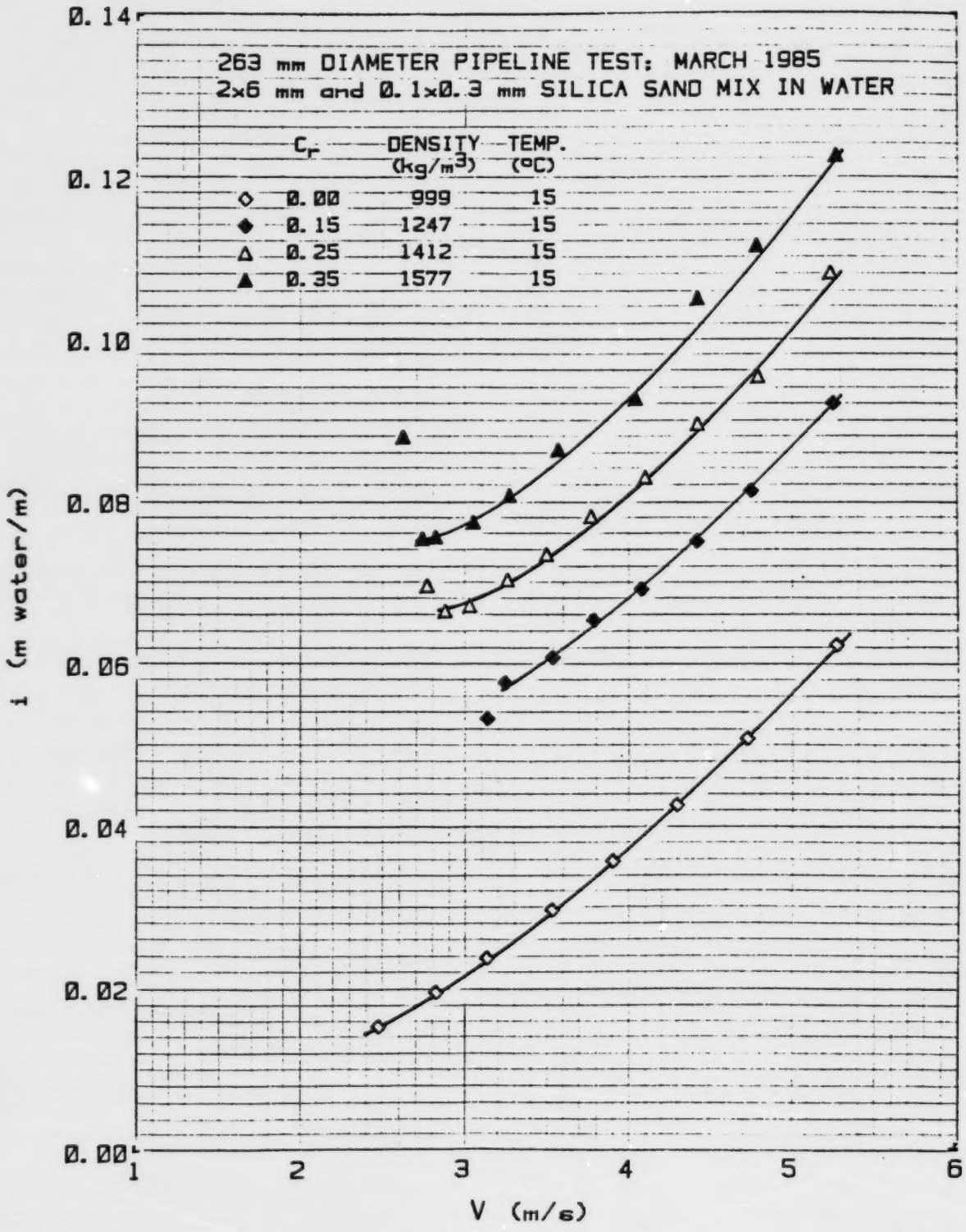



Figure 10. Headloss vs Velocity for Test Series #852506

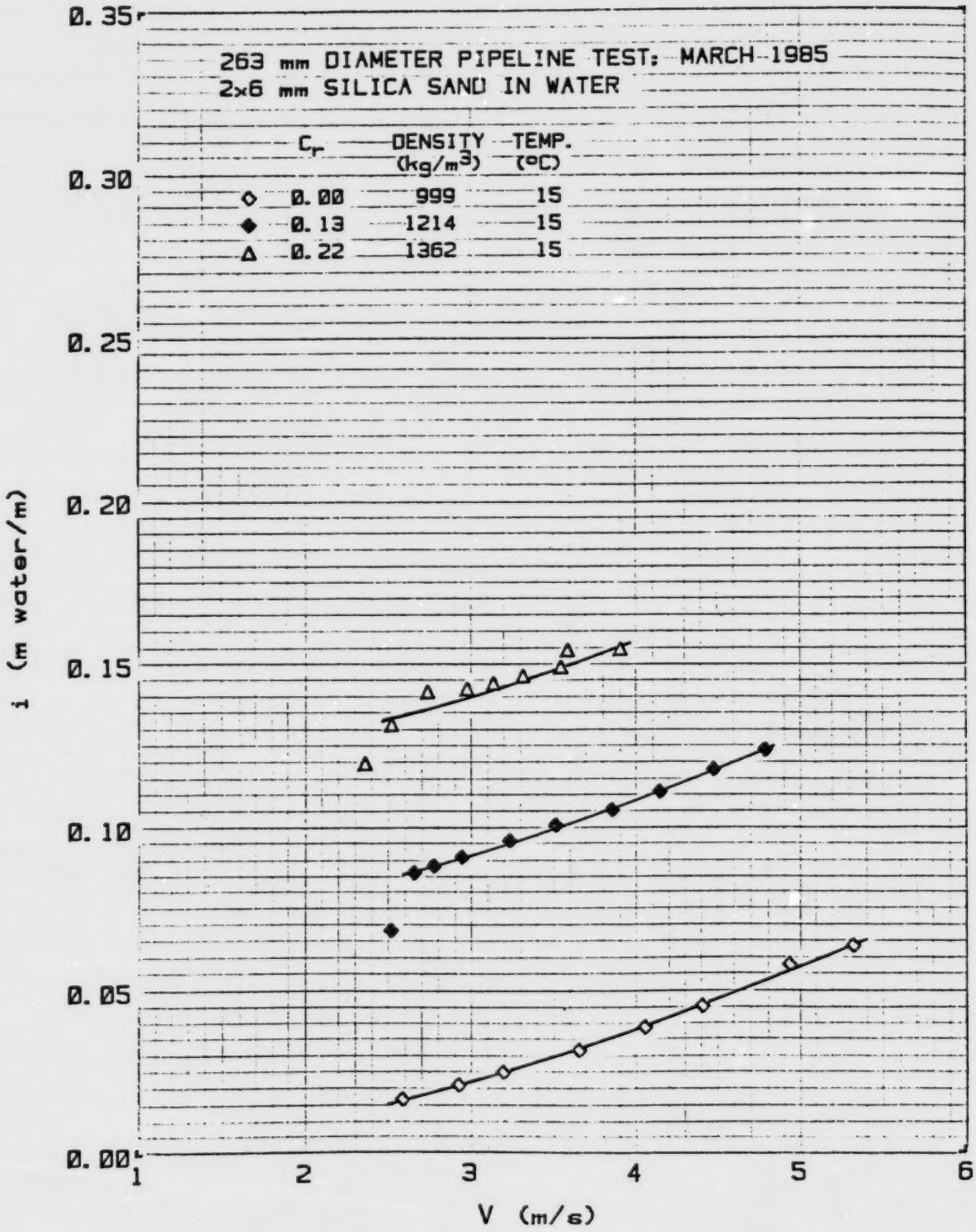



Figure 11. Headloss vs Velocity for Test Series #852507

section should be independent of velocity for the re-circulating loop. Possibly, the thickness of the stationary deposit varies along the test section. It is conceivable that the deposit forms first at the downstream pressure tapping since the upsteam tapping is nearer a flow disturbance point (a long radius elbow). If this is the case, part of the measured pressure differential would be due to the increased kinetic energy of the slurry at the downstream tapping.

Figure 12 gives an example of the performance of the bedding detector probe. As the pipeline velocity is reduced the fluctuations in the probe's electrical signal increase in magnitude due to increasing "macroturbulent" slurry concentration fluctuations near the bottom of the pipe. The fluctuations suddenly die out when a stationary deposit covers the probe. The probe's voltage output (mean and root mean square variation) is reported as a function of slurry velocity in Appendix B.

The carrier fluid viscosities were determined using a Brookfield concentric cylinder viscometer. The results of the viscosity measurements are tabulated in Appendix C.

Figures 13 to 17 show the effects of carrier properties on the slurry headlosses. As shown in Figures 13 and 14, the carrier temperature can affect the slurry behavior

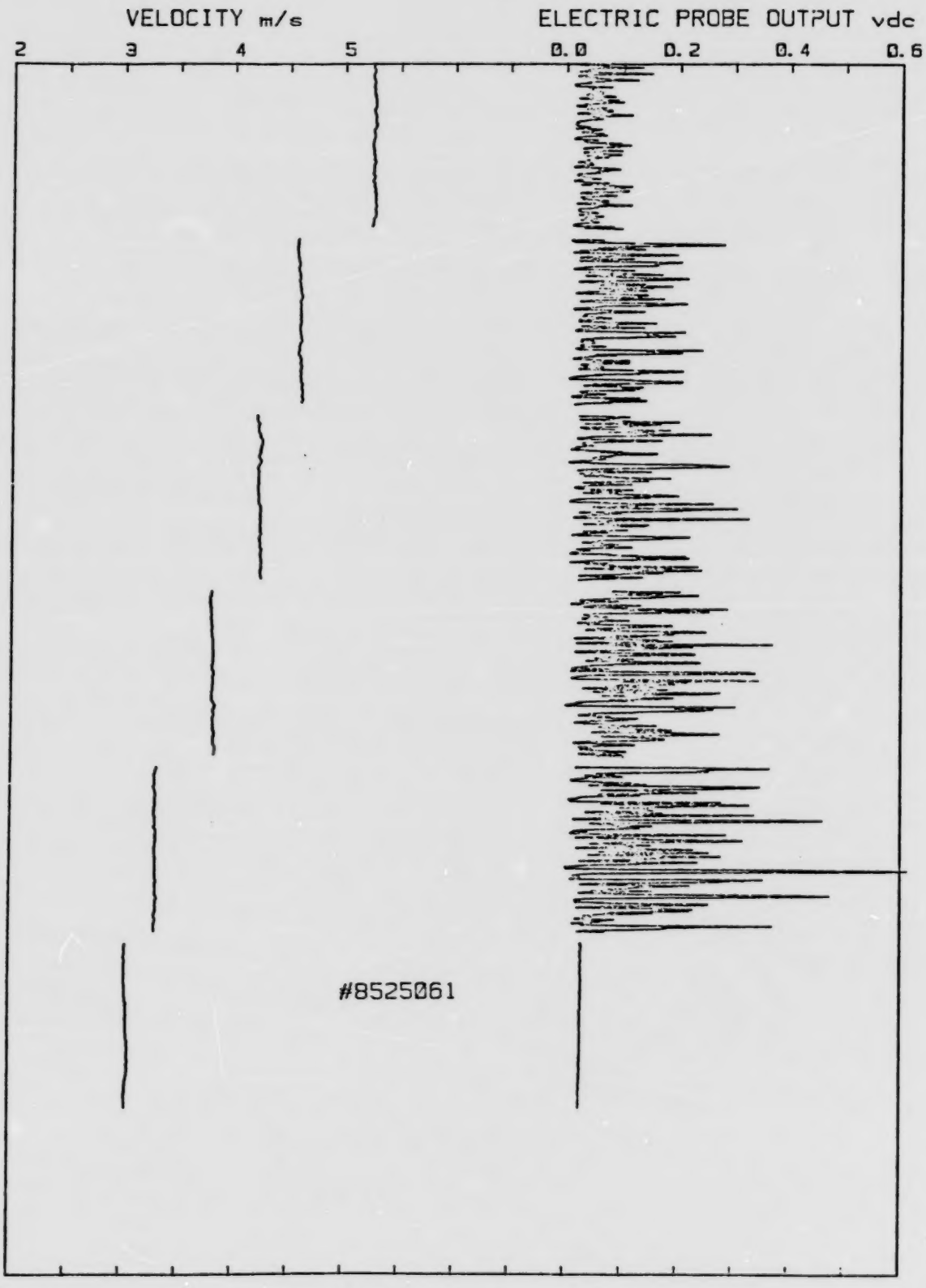



Figure 12. Bedding detector electric output.

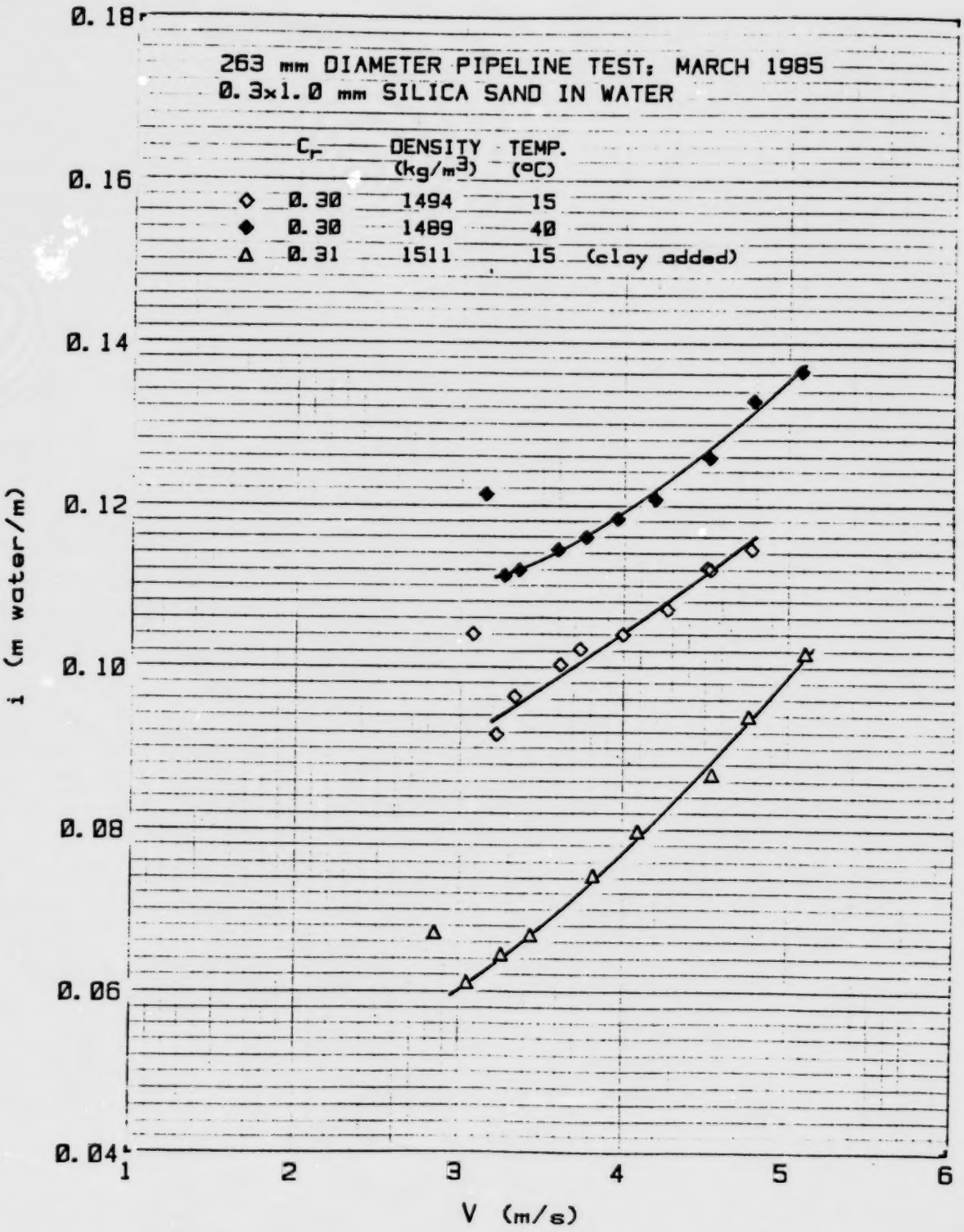



Figure 13. Effect of Carrier Properties on Headloss. #852503

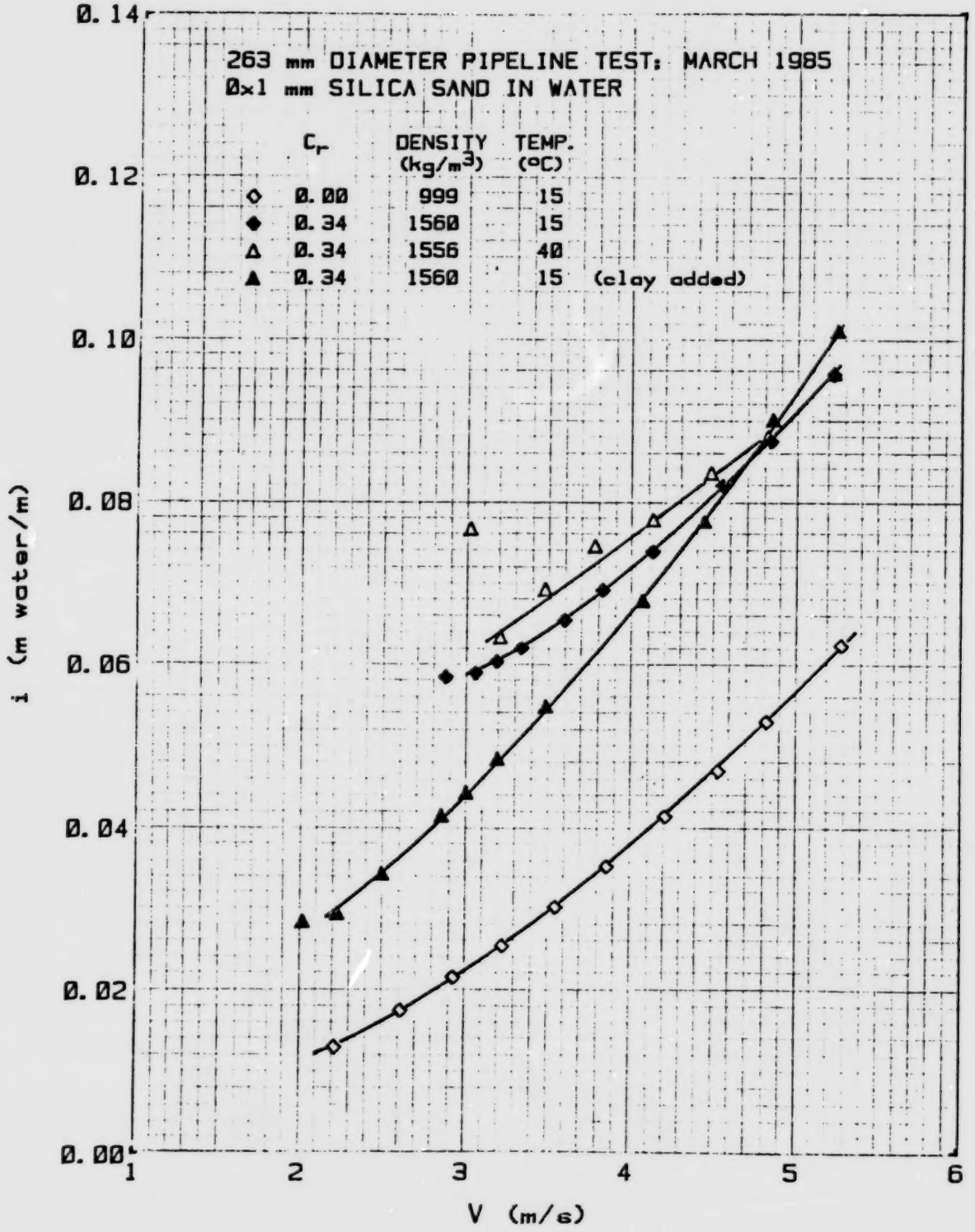



Figure 14. Effect of Carrier Properties on Headloss. #852504

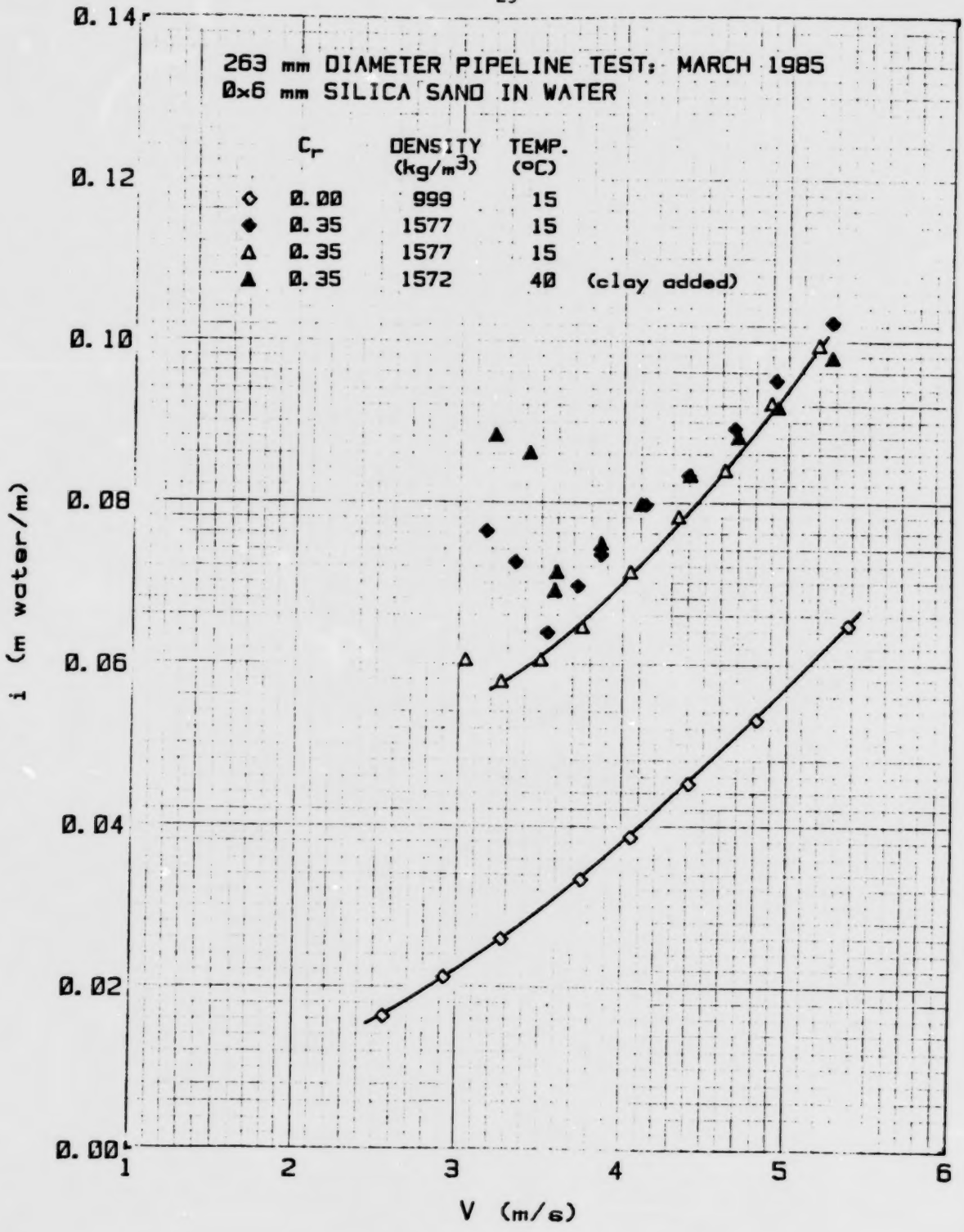



Figure 15. Effect of Carrier Properties on Headloss. #852505

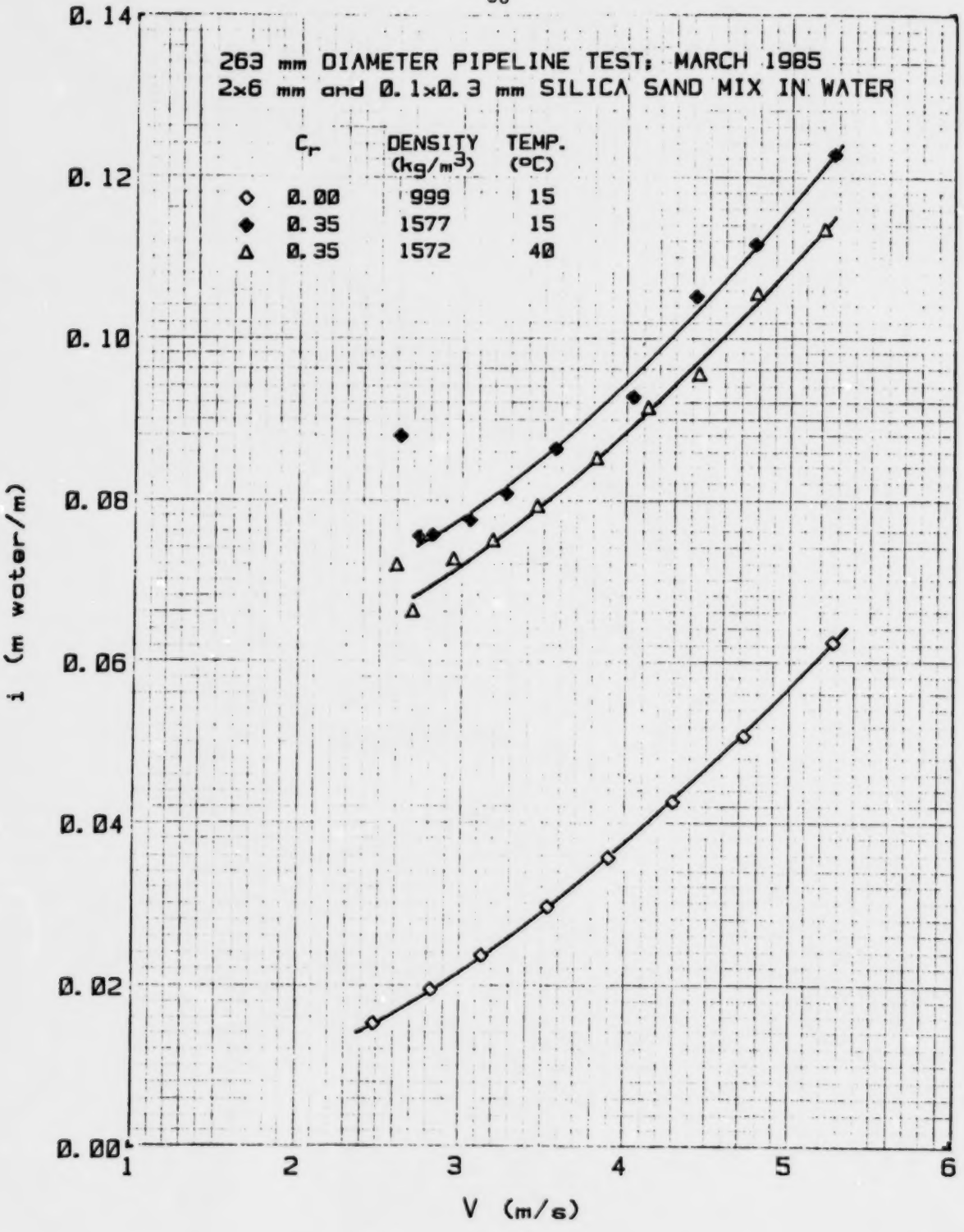



Figure 16. Effect of Carrier Properties on Headloss. #852506

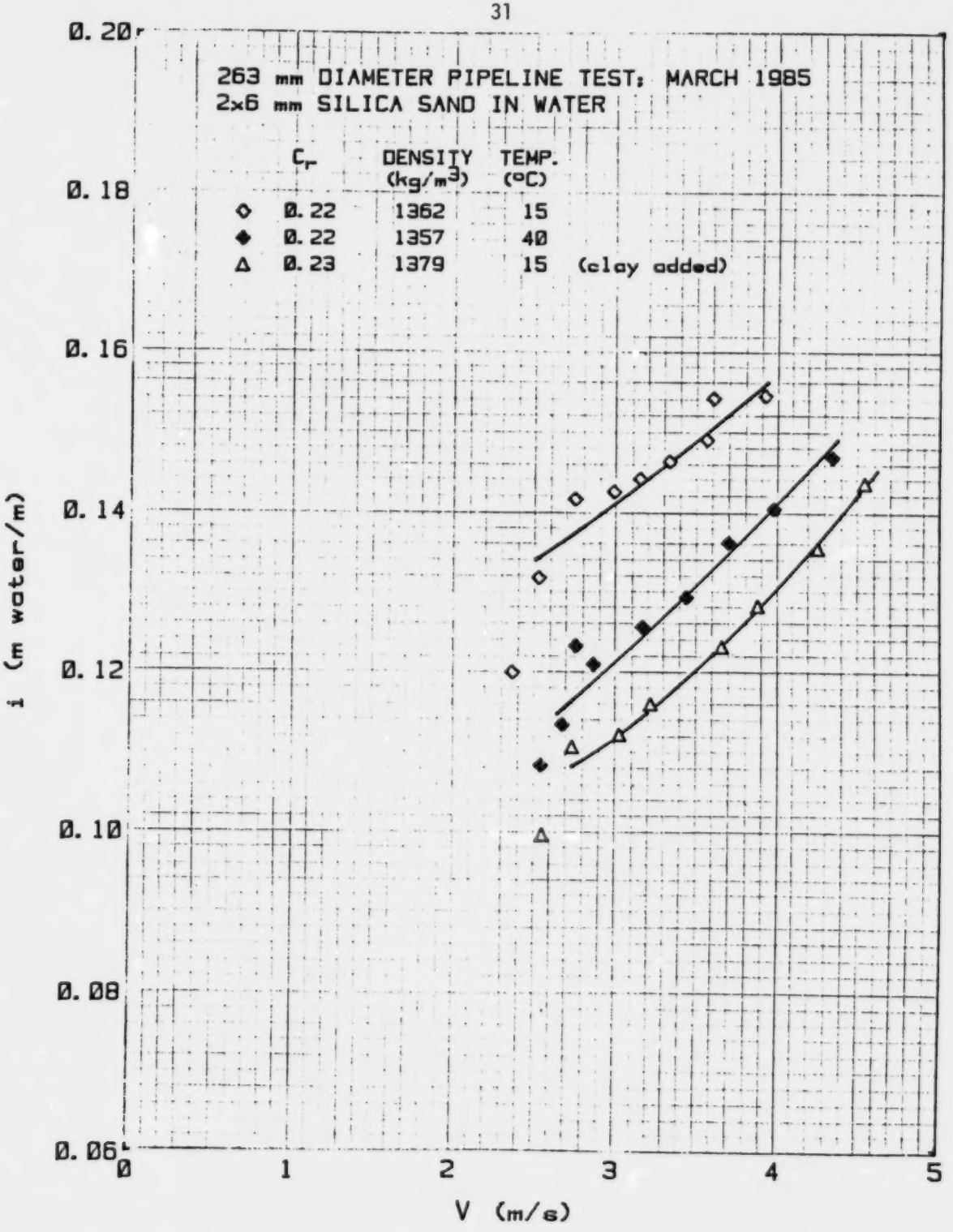



Figure 17. Effect of Carrier Properties on Headloss. #852507

significantly. The headloss at 40•C is considerably higher than the headloss at 15•C. This effect is generally attributed to the temperature dependence of the carrier fluid viscosity. At the elevated temperature, the carrier has a lower viscosity and a reduced ability to suspend solid particles. Clay addition resulted in an increased carrier viscosity and dropped the slurry headloss quite dramatically. However, slurries containing 2x6 mm gravel (Figures 16 and 17) showed decreased headlosses at the elevated temperature. This could be due to generation of silt-sized fines during re-circulation of the large diameter solids. The presence of fines would increase the effective density of the carrier fluid. However, unlike the clay, the silt-sized fines did not increase the carrier viscosity.

Delivered concentrations were inferred from measurements of local concentrations and local velocities. These measured delivered concentrations are compared to the delivered concentrations predicted by the two-layer model in Appendix D.

The results of particle drag coefficient determinations are given in Appendix E. Drag coefficient effects did not need to be considered to correlate the headlosses for the sand slurries with those for the coal slurries. Western Canadian coal particles tend to be rounded. Drag coefficient effects

would have to be considered for angular or plate-like solids.

Coefficients of kinematic friction were:

$\eta_s$ = 0.5 for sand on carbon steel

$\eta_s$ = 0.4 for coal on carbon steel.

3.2 Model improvement

The version of Wilson's two-layer model used in this study is based on in-situ solids concentrations and uses a constant composition lower layer. Appendix F gives details about the model and outlines how it may be applied to calculate slurry headlosses.

An analysis using important dimensionless groups was chosen to find an improved method for predicting the contact load, $C_c$ for slurries falling in the transition region between coarse-particle slurries and fine-particle slurries. For coarse-particle slurries, the entire solids load is transmitted to the pipe wall, whereas, for fine-particle slurries, the solids are completely suspended by fluid lift forces. Experimental results from the present study and from several previous studies were used to obtain a best fit equation for predicting $C_c$. It was found that the following correlation gave reasonable predictions for $C_c$ for a wide range of slurry pipelining conditions:

$$C_c = C_r \exp\{k1\ Ar^{k2}\ (V^2/gd)^{k3}\ (d/D)^{k4}\ (\rho_s/\rho_f - 1)^{k5}\}$$

where Ar = Archimedes number, $4\ g\ d^3\ \rho_f\ (\rho_s - \rho_f) / 3\ \mu_f^2$

g = acceleration of gravity

d = mass average particle diameter

D = pipe diameter

$\rho_f$ = carrier fluid density

$\rho_s$ = solids "effective" density

$\mu_f$ = carrier fluid viscosity

V = average slurry velocity

and the correlating constants

k1 = -0.124

k2 = -0.061

k3 = 0.028

k4 = -0.431

k5 = -0.272

Table 2 summarizes the data used in arriving at the correlation for contact load. The reported contact load values are inferred from experimental measurements of headloss. They are the contact load values required for the model to give accurate estimates for headloss. Figures 18 and 19 illustrated the goodness of fit for the contact load correlation. The "measured" contact load is inferred from the experimental data. The "calculated" contact load is predicted using the correlation.

Table 2. Slurry Pipeline Data Used in Contact Load Correlation

| D (m) | d (mm) | $\rho_s$ (kg/m$^3$) | $\rho_f$ (kg/m$^3$) | $\mu$ (cp) | $C_r$ | V (m/s) | $C_c/C_r$ experimental | $C_c/C_r$ correlation |
|---|---|---|---|---|---|---|---|---|
| | | 0.3 x 1.0 mm Silica Sand | | | | | | |
| 0.263 | 0.55 | 2650 | 999 | 1.3 | 0.15 | 3.66 | 0.313 | 0.300 |
| 0.263 | 0.55 | 2650 | 999 | 1.3 | 0.15 | 4.27 | 0.300 | 0.297 |
| 0.263 | 0.55 | 2650 | 999 | 1.3 | 0.15 | 5.18 | 0.267 | 0.293 |
| 0.263 | 0.55 | 2650 | 999 | 1.5 | 0.25 | 3.35 | 0.263 | 0.296 |
| 0.263 | 0.55 | 2650 | 999 | 1.5 | 0.25 | 3.96 | 0.292 | 0.293 |
| 0.263 | 0.55 | 2650 | 999 | 1.5 | 0.25 | 4.88 | 0.256 | 0.288 |
| 0.263 | 0.55 | 2650 | 999 | 1.6 | 0.30 | 3.35 | 0.307 | 0.293 |
| 0.263 | 0.55 | 2650 | 999 | 1.6 | 0.30 | 3.96 | 0.297 | 0.290 |
| 0.263 | 0.55 | 2650 | 999 | 1.6 | 0.30 | 4.88 | 0.263 | 0.286 |
| 0.263 | 0.55 | 2650 | 992 | 0.94 | 0.30 | 3.35 | 0.387 | 0.318 |
| 0.263 | 0.55 | 2650 | 992 | 0.94 | 0.30 | 3.96 | 0.373 | 0.314 |
| 0.263 | 0.55 | 2650 | 992 | 0.94 | 0.30 | 4.88 | 0.353 | 0.310 |
| | | 0 x 1 mm Silica Sand | | | | | | |
| 0.263 | 0.285 | 2650 | 999 | 1.3 | 0.15 | 3.05 | 0.152 | 0.163 |
| 0.263 | 0.285 | 2650 | 999 | 1.3 | 0.15 | 3.96 | 0.133 | 0.159 |
| 0.263 | 0.285 | 2650 | 999 | 1.3 | 0.15 | 5.18 | 0.08 | 0.154 |
| 0.263 | 0.285 | 2650 | 999 | 1.5 | 0.25 | 3.05 | 0.168 | 0.158 |
| 0.263 | 0.285 | 2650 | 999 | 1.5 | 0.25 | 3.96 | 0.124 | 0.153 |
| 0.263 | 0.285 | 2650 | 999 | 1.5 | 0.25 | 5.18 | 0.068 | 0.149 |
| 0.263 | 0.285 | 2650 | 999 | 1.77 | 0.35 | 3.05 | 0.154 | 0.152 |
| 0.263 | 0.285 | 2650 | 999 | 1.77 | 0.35 | 3.96 | 0.120 | 0.148 |
| 0.263 | 0.285 | 2650 | 999 | 1.77 | 0.35 | 5.18 | 0.069 | 0.143 |
| 0.263 | 0.285 | 2650 | 992 | 1.02 | 0.35 | 3.35 | 0.169 | 0.171 |
| 0.263 | 0.285 | 2650 | 992 | 1.02 | 0.35 | 4.27 | 0.140 | 0.167 |
| 0.263 | 0.285 | 2650 | 992 | 1.02 | 0.35 | 5.18 | 0.089 | 0.164 |
| | | 0 x 6 mm Silica Sand | | | | | | |
| 0.263 | 0.335 | 2650 | 999 | 1.3 | 0.15 | 3.35 | 0.222 | 0.193 |
| 0.263 | 0.335 | 2650 | 999 | 1.3 | 0.15 | 3.96 | 0.200 | 0.190 |
| 0.263 | 0.335 | 2650 | 999 | 1.3 | 0.15 | 5.18 | 0.153 | 0.185 |
| 0.263 | 0.335 | 2650 | 999 | 1.5 | 0.25 | 3.66 | 0.196 | 0.186 |
| 0.263 | 0.335 | 2650 | 999 | 1.5 | 0.25 | 4.27 | 0.164 | 0.183 |
| 0.263 | 0.335 | 2650 | 999 | 1.5 | 0.25 | 5.18 | 0.148 | 0.180 |
| 0.263 | 0.335 | 2650 | 999 | 1.77 | 0.35 | 3.66 | 0.140 | 0.180 |
| 0.263 | 0.335 | 2650 | 999 | 1.77 | 0.35 | 4.27 | 0.120 | 0.177 |
| 0.263 | 0.335 | 2650 | 999 | 1.77 | 0.35 | 5.18 | 0.086 | 0.174 |
| 0.263 | 0.335 | 2650 | 992 | 1.02 | 0.35 | 3.66 | 0.171 | 0.202 |
| 0.263 | 0.335 | 2650 | 992 | 1.02 | 0.35 | 4.27 | 0.146 | 0.199 |
| 0.263 | 0.335 | 2650 | 992 | 1.02 | 0.35 | 5.18 | 0.123 | 0.196 |
| | | 2 x 6 mm Silica Sand | | | | | | |
| 0.263 | 2.4 | 2650 | 999 | 1.5 | 0.13 | 3.35 | 0.620 | 0.624 |
| 0.263 | 2.4 | 2650 | 999 | 1.5 | 0.13 | 4.88 | 0.650 | 0.617 |
| 0.263 | 2.4 | 2650 | 999 | 2.0 | 0.22 | 3.05 | 0.632 | 0.615 |

Table 2. Slurry Pipeline Data Used in Contact Load Correlation (continued)

| D (m) | d (mm) | $\rho_s$ (kg/m$^3$) | $\rho_f$ (kg/m$^3$) | $\mu$ (cp) | $C_r$ | V (m/s) | $C_c/C_r$ experimental | $C_c/C_r$ correlation |
|---|---|---|---|---|---|---|---|---|
| 0.263 | 2.4 | 2650 | 999 | 2.0 | 0.22 | 3.96 | 0.619 | 0.610 |
| 0.263 | 2.4 | 2650 | 992 | 1.2 | 0.22 | 3.35 | 0.562 | 0.632 |
| 0.263 | 2.4 | 2650 | 992 | 1.2 | 0.22 | 4.27 | 0.564 | 0.628 |
| | | 0 x 10 mm Westar Coal | | | | | | |
| 0.263 | 0.8 | 1374 | 998 | 0.945 | 0.22 | 1.77 | 0.277 | 0.240 |
| 0.263 | 0.8 | 1374 | 998 | 0.945 | 0.22 | 2.61 | 0.232 | 0.232 |
| 0.263 | 0.8 | 1374 | 998 | 0.945 | 0.22 | 4.07 | 0.195 | 0.224 |
| 0.263 | 0.85 | 1374 | 1042 | 2.06 | 0.232 | 1.96 | 0.300 | 0.202 |
| 0.263 | 0.85 | 1374 | 1042 | 2.06 | 0.232 | 2.69 | 0.259 | 0.196 |
| 0.263 | 0.85 | 1374 | 1042 | 2.06 | 0.232 | 4.17 | 0.203 | 0.188 |
| 0.263 | 1.1 | 1374 | 1064 | 3.20 | 0.303 | 2.61 | 0.274 | 0.225 |
| 0.263 | 1.1 | 1374 | 1064 | 3.20 | 0.303 | 3.90 | 0.175 | 0.217 |
| 0.263 | 1.1 | 1374 | 1064 | 3.20 | 0.303 | 1.69 | 0.244 | 0.233 |
| | | 60/100 mesh Silica Sand | | | | | | |
| 0.263 | 0.19 | 2650 | 999 | 1.1 | 0.285 | 2.59 | 0.088 | 0.102 |
| 0.263 | 0.19 | 2650 | 999 | 1.1 | 0.285 | 3.05 | 0.084 | 0.099 |
| 0.263 | 0.19 | 2650 | 999 | 1.1 | 0.285 | 3.81 | 0.084 | 0.097 |
| 0.263 | 0.19 | 2650 | 999 | 1.0 | 0.380 | 2.59 | 0.103 | 0.104 |
| 0.263 | 0.19 | 2650 | 999 | 1.0 | 0.380 | 3.05 | 0.087 | 0.102 |
| 0.263 | 0.19 | 2650 | 999 | 1.0 | 0.380 | 3.81 | 0.103 | 0.099 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.208 | 4.46 | 0.05 | 0.062 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.208 | 4.58 | 0.05 | 0.062 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.208 | 4.69 | 0.05 | 0.062 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.277 | 4.38 | 0.07 | 0.063 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.277 | 4.46 | 0.067 | 0.062 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.277 | 4.62 | 0.065 | 0.062 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.356 | 4.41 | 0.090 | 0.063 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.356 | 4.50 | 0.093 | 0.062 |
| 0.495 | 0.19 | 2650 | 983 | 0.47 | 0.356 | 4.68 | 0.081 | 0.062 |
| 0.495 | 0.19 | 2650 | 999 | 1.2 | 0.347 | 2.90 | 0.037 | 0.047 |
| 0.495 | 0.19 | 2650 | 999 | 1.2 | 0.347 | 3.35 | 0.040 | 0.046 |
| 0.495 | 0.19 | 2650 | 999 | 1.2 | 0.347 | 4.27 | 0.052 | 0.044 |
| 0.1585 | 0.19 | 2650 | 999 | 1.3 | 0.15 | 2.33 | 0.127 | 0.155 |
| 0.1585 | 0.19 | 2650 | 999 | 1.3 | 0.15 | 2.72 | 0.120 | 0.152 |
| 0.1585 | 0.19 | 2650 | 999 | 1.3 | 0.15 | 3.59 | 0.067 | 0.148 |
| 0.1585 | 0.19 | 2650 | 999 | 1.3 | 0.30 | 2.15 | 0.127 | 0.156 |
| 0.1585 | 0.19 | 2650 | 999 | 1.3 | 0.30 | 2.59 | 0.133 | 0.153 |
| 0.1585 | 0.19 | 2650 | 999 | 1.3 | 0.30 | 3.77 | 0.147 | 0.147 |
| 0.1585 | 0.19 | 2650 | 983 | 0.47 | 0.15 | 2.50 | 0.200 | 0.193 |
| 0.1585 | 0.19 | 2650 | 983 | 0.47 | 0.15 | 3.12 | 0.190 | 0.189 |
| 0.1585 | 0.19 | 2650 | 983 | 0.47 | 0.15 | 3.93 | 0.113 | 0.185 |
| 0.1585 | 0.19 | 2650 | 983 | 0.47 | 0.30 | 2.75 | 0.215 | 0.192 |
| 0.1585 | 0.19 | 2650 | 983 | 0.47 | 0.30 | 3.15 | 0.200 | 0.189 |
| 0.1585 | 0.19 | 2650 | 983 | 0.47 | 0.30 | 3.94 | 0.167 | 0.185 |
| 0.0525 | 0.19 | 2650 | 984 | 0.47 | 0.18 | 3.11 | 0.222 | 0.356 |

Table 2. Slurry Pipeline Data Used in Contact Load Correlation (continued)

| D (m) | d (mm) | $\rho_s$ (kg/m$^3$) | $\rho_f$ (kg/m$^3$) | $\mu$ (cp) | Cr | V (m/s) | $C_c/C_r$ experimental | $C_c/C_r$ correlation |
|---|---|---|---|---|---|---|---|---|
| 0.0525 | 0.19 | 2650 | 984 | 0.47 | 0.18 | 2.25 | 0.322 | 0.362 |
| 0.0525 | 0.19 | 2650 | 984 | 0.47 | 0.18 | 1.68 | 0.367 | 0.368 |
| 0.0525 | 0.19 | 2650 | 984 | 0.47 | 0.36 | 3.11 | 0.261 | 0.356 |
| 0.0525 | 0.19 | 2650 | 984 | 0.47 | 0.36 | 2.25 | 0.294 | 0.362 |
| 0.0525 | 0.19 | 2650 | 984 | 0.47 | 0.36 | 1.68 | 0.300 | 0.368 |
| 0.0525 | 0.19 | 2650 | 998 | 0.98 | 0.18 | 3.11 | 0.261 | 0.321 |
| 0.0525 | 0.19 | 2650 | 998 | 0.98 | 0.18 | 2.25 | 0.294 | 0.327 |
| 0.0525 | 0.19 | 2650 | 998 | 0.98 | 0.18 | 1.68 | 0.300 | 0.333 |
| 0.0525 | 0.19 | 2650 | 998 | 0.98 | 0.36 | 3.11 | 0.356 | 0.321 |
| 0.0525 | 0.19 | 2650 | 998 | 0.98 | 0.36 | 2.25 | 0.350 | 0.327 |
| 0.0525 | 0.19 | 2650 | 998 | 0.98 | 0.36 | 1.68 | 0.330 | 0.333 |
| 0.0525 | 0.19 | 2650 | 1000 | 1.30 | 0.18 | 3.11 | 0.306 | 0.308 |
| 0.0525 | 0.19 | 2650 | 1000 | 1.30 | 0.18 | 2.25 | 0.306 | 0.314 |
| 0.0525 | 0.19 | 2650 | 1000 | 1.30 | 0.18 | 1.68 | 0.272 | 0.320 |
| 0.0525 | 0.19 | 2650 | 1000 | 1.30 | 0.36 | 3.11 | 0.408 | 0.308 |
| 0.0525 | 0.19 | 2650 | 1000 | 1.30 | 0.36 | 2.25 | 0.389 | 0.314 |
| 0.0525 | 0.29 | 2650 | 1000 | 1.30 | 0.36 | 1.58 | 0.322 | 0.322 |
| | | 30/50 mesh Silica Sand | | | | | | |
| 0.0525 | 0.49 | 2650 | 998 | 0.98 | 0.18 | 3.40 | 0.467 | 0.537 |
| 0.0525 | 0.49 | 2650 | 998 | 0.98 | 0.18 | 2.25 | 0.639 | 0.545 |
| 0.0525 | 0.49 | 2650 | 998 | 0.98 | 0.18 | 1.68 | 0.650 | 0.550 |
| 0.0525 | 0.49 | 2650 | 998 | 0.98 | 0.30 | 3.41 | 0.544 | 0.537 |
| 0.0525 | 0.49 | 2650 | 998 | 0.98 | 0.30 | 2.25 | 0.622 | 0.545 |
| 0.0525 | 0.49 | 2650 | 998 | 0.98 | 0.30 | 1.68 | 0.656 | 0.550 |

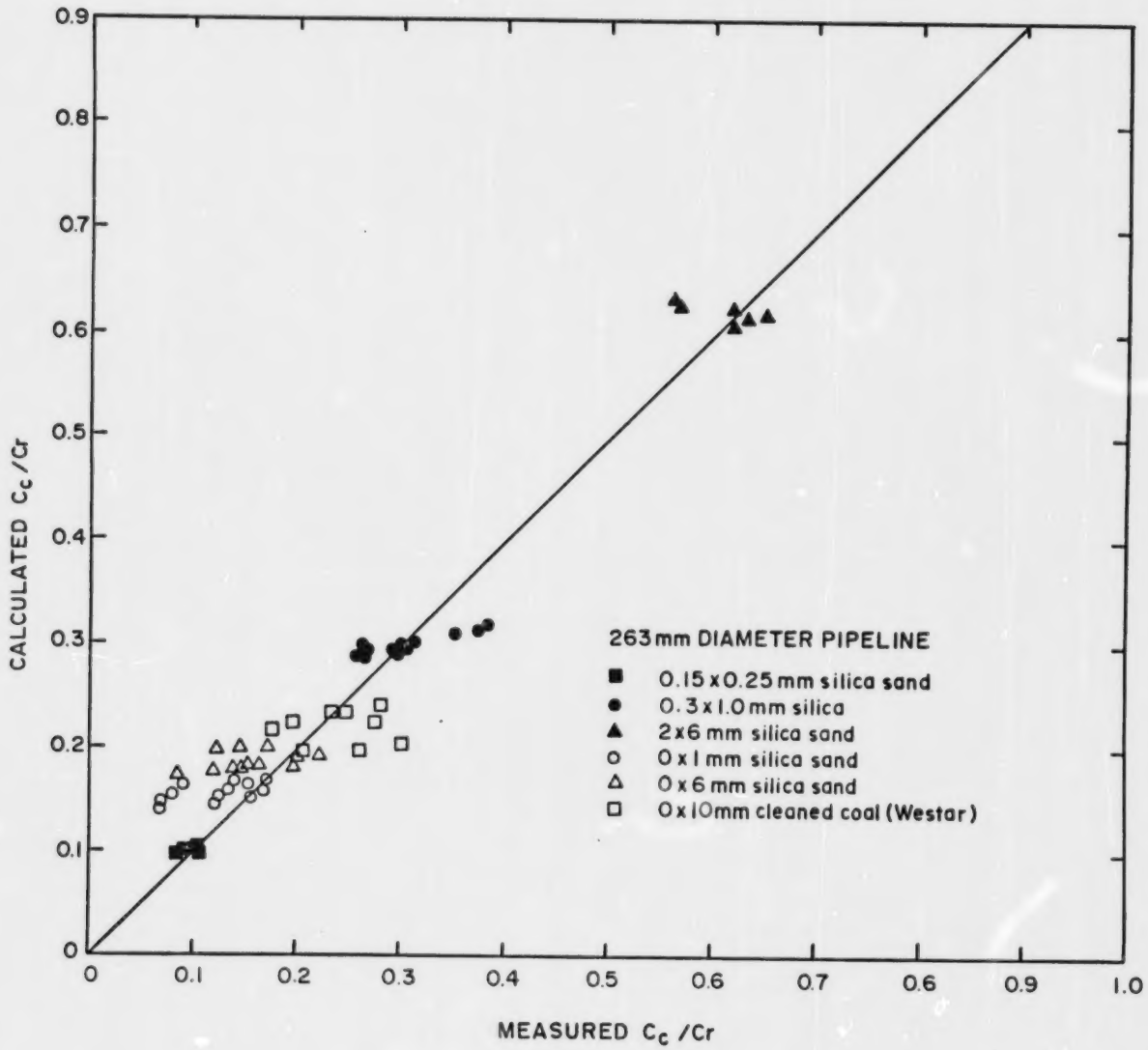



Figure 18. Contact load predictions for slurries in a 263 mm pipeline.

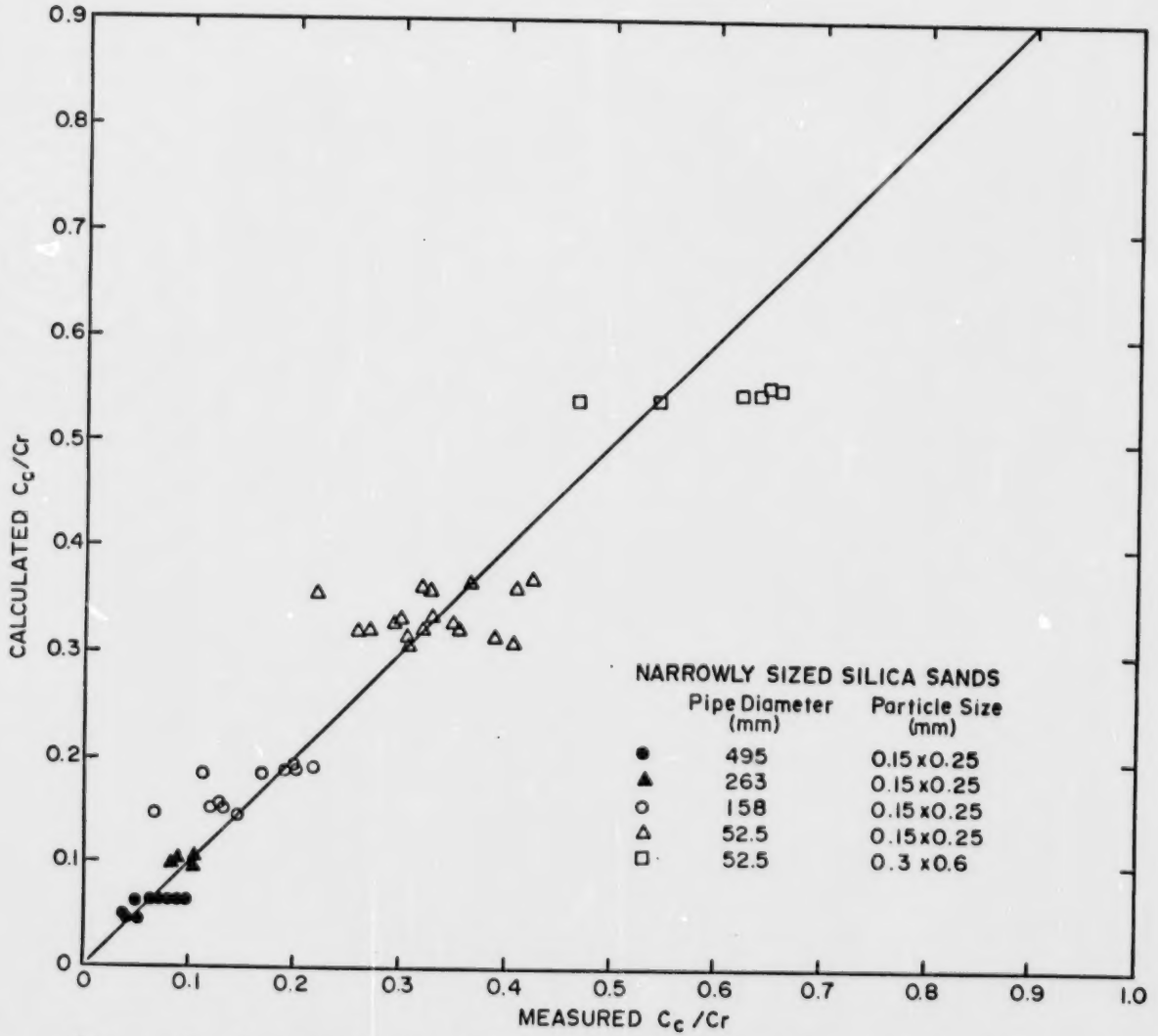



Figure 19. Contact load predictions for narrowly sized sand slurries.

With the new predictive equation for contact load, the two-layer model should be useful for examining a variety of slurry pipeline engineering problems. In the absence of pipeline loop test data, the model will provide reasonably accurate headloss estimates for feasibility studies and for preliminary design. The model will also be useful for estimating the effects of changes in the operating conditions for existing systems.

The form of the correlation was chosen to give reasonable contact load predictions for extreme values of the independent variables. Intuitively one would expect the ratio $C_c/C_r$ to approach one when:

- -slurry velocity approaches zero,
- -carrier fluid viscosity is low,
- -solid/fluid density ratio is high,
- -particle diameter is large.

Also, one would expect the contact load to approach zero when:

- -slurry velocity is very high,
- -carrier fluid viscosity is high,
- -solids/fluid density ratio approaches one,
- -particles are very small.

The correlation shows that pipe size has a large effect on contact load. However, it should be noted that the only suitable data available for examining pipe size effects was

for fine sand (0.15x 0.25 mm). The remaining phases of the present study will provide information for coarser materials in 100mm and 500 mm diameter pipeline loops. By comparing the results of the future work with the data presented in this report, it should be possible to determine the effects of pipe size with confidence.

Delivered concentrations from the model were in reasonable agreement with those calculated from the particle velocities and concentrations, except for the coarsest particles (Appendix D). To improve the agreement, the interfacial friction factor $f_{12}$ in the model should be increased for slurries containing very coarse particles. The tests to be conducted in the remaining phases of the program should provide the data required to make the modification to the interfacial friction factor.

The two-layer model is useful for correlating critical deposition velocities. The model often predicts lower layer velocities near zero for mean velocities near deposition.

## 4. CONCLUSIONS AND RECOMMENDATIONS

1. The fluid viscosity, rather than slurry viscosity, appears to determine the contact load fraction of the mixture (at least for mixtures containing less than 35% solids by volume).

2. The in-situ volumetric concentration, rather than the delivered concentration, has been shown to be the appropriate parameter for use in the model.

3. For solids with a size distribution of moderate breadth, the mass mean particle diameter ($d_{50}$) is the appropriate parameter.

4. The tests have provided results for a range of particle sizes (to 6 mm) in a 250 mm pipeline.

5. Existing data provide information on the effect of pipe diameter only for slurries with relatively fine particles (sand with a $d_{50}$ of 0.18 mm).

6. The ratio of particle diameter to pipe diameter is of considerable importance in determining the contact load. This effect is much greater than previously indicated.

7. A tentative correlation for the prediction of contact load has been obtained using the data in items 4 and 5. This correlation is most reliable in the region covered by

the present experiments. Further work, involving pipes of other sizes, is required to extend the range of applicability of the model.

8. In contrast with clay-water mixtures, clay-water-sand slurries exhibit complex rheology in some cases.

9. Even though the two-layer model is effective for predicting headlosses, measurements of local velocities and concentrations show that the model is based on a simplified picture of slurry flow in pipelines. The velocity profiles and concentration profiles reported in Appendix A should provide a basis for understanding the mechanisms by which solids are suspended in horizontal pipelines.

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## SYMBOLS

$A$ = cross-sectional area of pipe

$c$ = local solids volume fraction

$C_c$ = contact solids volume fraction

$C_D$ = particle drag coefficient

$C_r$ = average in-situ solids volume fraction

$C_{vd}$ = solids volume fraction in delivered mixture

$d$ = particle diameter

$D$ = pipe internal diameter

$f$ = Fanning friction factor

$g$ = gravitational acceleration

$i$ = headloss gradient due to flow (m of water/m of pipe)

$L$ = pipe chord length for gamma ray gauge scan

$Re$ = Reynolds number

$S$ = surface length defined in Figure 20

$v$ = local particle velocity

$V$ = average slurry velocity

$V_p$ = average particle velocity

$V_t$ = terminal settling velocity of a particle

$y$ = distance measured vertically from bottom of pipe

$\beta$ = angular position in pipe defined in Figure 20

$\epsilon$ = effective roughness of pipe wall

$\rho$ = density

$\tau$ = shear stress

$\mu$ = dynamic viscosity

Subscripts:

1 = upper layer

2 = lower layer

12 = interface value

d = delivered

f = fluid

j = position in pipe cross-section

s = solid

r = in-situ

w = water

# APPENDIX A: HYDRAULIC TEST DATA

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525030
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0.3x1.0 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 998
SLURRY DENSITY (kg/cu m): 998
SOLIDS VOLUME FRACTION: 0.00

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.19 | 4.65 | 4.13 | 3.58 | 3.08 | 2.49 | 1.78 |
|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0632 | 0.0516 | 0.0412 | 0.0315 | 0.0239 | 0.0161 | 0.0086 |
| Deposit | --- | --- | --- | --- | --- | --- | --- |

INT = intermittent deposit. STA = stationary deposit.

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525031
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0.3x1.0 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1247
SOLIDS VOLUME FRACTION: 0.15

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.20 | 4.98 | 4.53 | 4.24 | 3.91 | 3.61 | 3.31 |
|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0918 | 0.0879 | 0.0801 | 0.0751 | 0.0697 | 0.0659 | 0.0666 |
| Deposit | --- | --- | --- | --- | --- | --- | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Hm) | 74 | 210 | 297 | 420 | 595 | 841 | 1190 | 2380 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.007 | 0.008 | 0.039 | 0.237 | 0.674 | 0.891 | 0.962 | 1.000 |
| PSD # 2 | 0.015 | 0.036 | 0.063 | 0.193 | 0.612 | 0.860 | 0.974 | 1.000 |

PSD # 1 Head sample

PSD # 2 Pipeline discharge sample after run

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.94 | 0.481 | 0.430 | 0.311 | 0.210 | 0.111 | 0.043 | 0.019 | 0.011 | 0.008 | 0.013 | 0.152 |
| 4.37 | 0.483 | 0.423 | 0.317 | 0.210 | 0.100 | 0.050 | 0.021 | 0.015 | 0.014 | 0.010 | 0.153 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.21 | 5.03 | 5.02 | 5.00 | 4.40 | 3.64 | 2.98 | 2.56 | 1.97 | 5.90 | 4.88 | 3.98 | 3.40 | 4.74 |
| 4.67 | 5.56 | 5.28 | 5.21 | 4.72 | 4.06 | 3.32 | 2.94 | 2.59 | 6.01 | 5.34 | 4.47 | 3.80 | 4.87 |
| 4.66 | 5.03 | 4.97 | 4.97 | 4.65 | 4.11 | 3.51 | 3.06 | 2.62 | 5.84 | 5.47 | 4.65 | 4.11 | 5.21 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525032
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0.3x1.0 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1412
SOLIDS VOLUME FRACTION: 0.25

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.92 | 4.60 | 4.35 | 4.07 | 3.83 | 3.45 | 3.60 | 3.41 | 3.32 | 3.12 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1047 | 0.1010 | 0.0962 | 0.0930 | 0.0893 | 0.0856 | 0.0867 | 0.0845 | 0.0830 | 0.0885 |
| Deposit | --- | --- | --- | --- | INT | INT | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 297 | 420 | 595 | 841 | 1190 | 2380 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.021 | 0.041 | 0.074 | 0.197 | 0.615 | 0.875 | 0.979 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.90 | 0.502 | 0.494 | 0.437 | 0.369 | 0.287 | 0.191 | 0.095 | 0.041 | 0.018 | 0.008 | 0.246 |
| 4.38 | 0.508 | 0.508 | 0.424 | 0.365 | 0.294 | 0.198 | 0.097 | 0.043 | 0.020 | 0.015 | 0.249 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.17 | 4.91 | 4.91 | 4.57 | 3.89 | 3.39 | 2.94 | 2.48 | 1.92 | 5.47 | 4.64 | 3.95 | 3.52 | 4.36 |
| 4.68 | 5.54 | 5.33 | 5.14 | 4.36 | 3.89 | 3.35 | 2.77 | 2.29 | 6.00 | 5.33 | 4.36 | 4.11 | 5.14 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525033
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0.3x1.0 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1494
SOLIDS VOLUME FRACTION: 0.30

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.78 | 4.51 | 4.27 | 4.00 | 4.53 | 3.74 | 3.62 | 3.34 | 3.23 | 3.08 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1145 | 0.1122 | 0.1071 | 0.1040 | 0.1120 | 0.1022 | 0.1003 | 0.0964 | 0.0917 | 0.1041 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | --- | --- | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Um) | 74 | 210 | 297 | 420 | 595 | 841 | 1190 | 2380 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.014 | 0.031 | 0.059 | 0.180 | 0.598 | 0.842 | 0.953 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.90 | 0.528 | 0.519 | 0.469 | 0.423 | 0.359 | 0.277 | 0.163 | 0.080 | 0.031 | 0.015 | 0.294 |
| 4.34 | 0.513 | 0.508 | 0.463 | 0.423 | 0.363 | 0.278 | 0.172 | 0.082 | 0.040 | 0.010 | 0.294 |
| 0.00 | 0.620 | 0.650 | 0.654 | 0.645 | 0.655 | 0.006 | 0.004 | 0.002 | 0.002 | 0.004 | 0.332 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.17 | 5.14 | 4.97 | 4.57 | 4.00 | 3.65 | 3.10 | 2.25 | 2.16 | 5.33 | 4.72 | 4.17 | 3.60 | 4.64 |
| 4.64 | 5.54 | 5.30 | 4.93 | 4.36 | 4.00 | 3.60 | 2.94 | 2.28 | 5.92 | 5.12 | 4.65 | 4.24 | 5.06 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525034
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0.3x1.0 mm SILICA SAND
CARRIER: WATER AND 0.5% CLAY

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1511
SOLIDS VOLUME FRACTION: 0.31

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.11 | 4.77 | 4.55 | 4.10 | 3.83 | 3.45 | 3.27 | 3.06 | 2.86 |
|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1017 | 0.0939 | 0.0867 | 0.0797 | 0.0742 | 0.0669 | 0.0645 | 0.0610 | 0.0672 |
| Deposit | --- | --- | --- | --- | --- | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 297 | 420 | 595 | 841 | 1190 | 2380 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.039 | 0.055 | 0.082 | 0.200 | 0.619 | 0.873 | 0.979 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.92 | 0.477 | 0.475 | 0.423 | 0.398 | 0.370 | 0.315 | 0.227 | 0.136 | 0.083 | 0.046 | 0.305 |
| 4.35 | 0.466 | 0.452 | 0.421 | 0.395 | 0.354 | 0.308 | 0.239 | 0.161 | 0.108 | 0.070 | 0.306 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.19 | 4.57 | 4.50 | 4.00 | 3.65 | 3.39 | 3.06 | 2.44 | 2.40 | 4.97 | 4.43 | 3.84 | 3.56 | 4.24 |
| 4.65 | 4.50 | 4.36 | 4.24 | 3.84 | 3.60 | 3.35 | 3.06 | 2.97 | 5.05 | 4.72 | 4.06 | 3.79 | 4.43 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525035
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 40
SOLIDS: 0.3x1.0 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 992
SLURRY DENSITY (kg/cu m):1489
SOLIDS VOLUME FRACTION: 0.30

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.08 | 4.79 | 4.52 | 4.19 | 3.96 | 3.77 | 3.60 | 3.36 | 3.27 | 3.15 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1364 | 0.1328 | 0.1259 | 0.1207 | 0.1183 | 0.1160 | 0.1145 | 0.1120 | 0.1113 | 0.1213 |
| Deposit | --- | --- | --- | --- | --- | --- | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 297 | 420 | 595 | 841 | 1190 | 2380 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.021 | 0.041 | 0.072 | 0.211 | 0.637 | 0.873 | 0.980 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.95 | 0.554 | 0.529 | 0.474 | 0.440 | 0.357 | 0.271 | 0.173 | 0.091 | 0.050 | 0.022 | 0.302 |
| 4.38 | 0.545 | 0.536 | 0.475 | 0.428 | 0.358 | 0.279 | 0.168 | 0.092 | 0.046 | 0.020 | 0.301 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.22 | 5.21 | 5.15 | 4.36 | 4.23 | 3.79 | 3.06 | 2.54 | 1.66 | 5.34 | 4.80 | 4.24 | 3.60 | 4.65 |
| 4.68 | 5.62 | 5.34 | 5.00 | 4.57 | 4.24 | 3.43 | 2.80 | 2.22 | 5.80 | 5.24 | 4.72 | 3.95 | 5.10 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525040
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0.1 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m): 999
SOLIDS VOLUME FRACTION: 0.00

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.28 | 4.83 | 4.54 | 4.22 | 3.87 | 3.56 | 3.24 | 2.94 | 2.62 | 2.22 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0621 | 0.0527 | 0.0467 | 0.0412 | 0.0351 | 0.0301 | 0.0253 | 0.0214 | 0.0174 | 0.0130 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |

INT = intermittent deposit. STA = stationary deposit.

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525041
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x1 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1263
SOLIDS VOLUME FRACTION: 0.16

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.27 | 4.82 | 4.38 | 4.10 | 3.77 | 3.46 | 3.23 | 3.01 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0760 | 0.0669 | 0.0590 | 0.0545 | 0.0494 | 0.0451 | 0.0424 | 0.0424 |
| Deposit | --- | --- | --- | --- | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.007 | 0.055 | 0.232 | 0.502 | 0.711 | 0.890 | 0.960 | 1.000 |
| PSD # 2 | 0.004 | 0.084 | 0.296 | 0.531 | 0.722 | 0.880 | 0.964 | 1.000 |

PSD # 1 Head sample

PSD # 2 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.94 | 0.435 | 0.399 | 0.307 | 0.221 | 0.131 | 0.073 | 0.045 | 0.033 | 0.028 | 0.025 | 0.162 |
| 4.68 | 0.408 | 0.356 | 0.282 | 0.211 | 0.131 | 0.086 | 0.053 | 0.038 | 0.029 | 0.024 | 0.155 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.21 | 4.59 | 4.52 | 4.44 | 4.24 | 3.84 | 3.37 | 3.01 | 2.92 | 5.26 | 4.95 | 4.38 | 3.89 | 4.80 |
| 5.00 | 5.26 | 5.10 | 5.01 | 4.90 | 4.52 | 4.18 | 3.89 | 3.78 | 6.01 | 5.68 | 5.19 | 4.86 | 5.76 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525042
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x1 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1412
SOLIDS VOLUME FRACTION: 0.25

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.22 | 4.79 | 4.39 | 4.09 | 3.76 | 3.49 | 3.22 | 3.07 | 2.97 |
|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0846 | 0.0753 | 0.0678 | 0.0629 | 0.0582 | 0.0545 | 0.0507 | 0.0506 | 0.0512 |
| Deposit | --- | --- | --- | --- | --- | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.009 | 0.085 | 0.295 | 0.531 | 0.730 | 0.887 | 0.966 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.95 | 0.470 | 0.447 | 0.401 | 0.367 | 0.292 | 0.222 | 0.120 | 0.062 | 0.038 | 0.029 | 0.248 |
| 4.65 | 0.440 | 0.431 | 0.378 | 0.342 | 0.273 | 0.209 | 0.137 | 0.089 | 0.057 | 0.046 | 0.243 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.22 | 4.87 | 4.79 | 4.55 | 4.04 | 3.63 | 3.45 | 3.16 | 3.12 | 5.51 | 4.86 | 4.34 | 3.99 | 4.79 |
| 4.97 | 5.32 | 5.28 | 5.09 | 4.62 | 4.52 | 4.24 | 4.06 | 4.00 | 6.18 | 5.60 | 5.15 | 4.94 | 5.68 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525043
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x1 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1560
SOLIDS VOLUME FRACTION: 0.34

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.22 | 4.84 | 4.55 | 4.13 | 3.83 | 3.60 | 3.34 | 3.19 | 3.06 | 2.88 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0954 | 0.0872 | 0.0818 | 0.0737 | 0.0690 | 0.0653 | 0.0619 | 0.0602 | 0.0588 | 0.0583 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.009 | 0.076 | 0.266 | 0.501 | 0.707 | 0.878 | 0.962 | 0.990 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.98 | 0.482 | 0.485 | 0.446 | 0.432 | 0.385 | 0.365 | 0.294 | 0.198 | 0.111 | 0.074 | 0.339 |
| 4.68 | 0.460 | 0.458 | 0.429 | 0.415 | 0.384 | 0.355 | 0.282 | 0.208 | 0.153 | 0.097 | 0.335 |
| 0.00 | 0.652 | 0.662 | 0.656 | 0.664 | 0.659 | 0.014 | 0.011 | 0.005 | 0.004 | 0.000 | 0.340 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.25 | 4.67 | 4.44 | 4.24 | 4.00 | 3.84 | 3.59 | 3.41 | 3.37 | 5.12 | 4.69 | 4.44 | 4.31 | 4.83 |
| 5.00 | 5.25 | 5.09 | 4.88 | 4.49 | 4.59 | 4.31 | 4.24 | 4.12 | 5.96 | 5.45 | 5.22 | 5.09 | 5.64 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525044
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x1 mm SILICA SAND
CARRIER: WATER AND 0.5% CLAY

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1560
SOLIDS VOLUME FRACTION: 0.34

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.24 | 4.85 | 4.44 | 4.07 | 3.49 | 3.20 | 3.01 | 2.86 | 2.50 | 2.23 | 2.02 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1008 | 0.0899 | 0.0774 | 0.0677 | 0.0547 | 0.0483 | 0.0442 | 0.0414 | 0.0343 | 0.0294 | 0.0284 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.028 | 0.092 | 0.304 | 0.524 | 0.720 | 0.882 | 0.966 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.11 | 0.417 | 0.419 | 0.392 | 0.388 | 0.365 | 0.349 | 0.319 | 0.290 | 0.259 | 0.191 | 0.345 |
| 4.70 | 0.399 | 0.392 | 0.375 | 0.360 | 0.331 | 0.327 | 0.305 | 0.278 | 0.256 | 0.217 | 0.327 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.32 | 3.22 | 3.18 | 3.18 | 3.15 | 2.98 | 2.80 | 2.72 | 2.69 | 4.00 | 3.84 | 3.54 | 3.41 | 3.84 |
| 5.02 | 4.83 | 4.72 | 4.80 | 4.75 | 4.64 | 4.52 | 4.38 | 4.31 | 5.68 | 5.60 | 5.42 | 5.22 | 6.00 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525045
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 40
SOLIDS: 0x1 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 992
SLURRY DENSITY (kg/cu m):1556
SOLIDS VOLUME FRACTION: 0.34

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.22 | 4.82 | 4.48 | 4.13 | 3.78 | 3.48 | 3.21 | 3.02 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0956 | 0.0878 | 0.0833 | 0.0776 | 0.0744 | 0.0691 | 0.0632 | 0.0765 |
| Deposit | --- | --- | --- | --- | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 |
|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.008 | 0.077 | 0.288 | 0.514 | 0.715 | 0.880 | 0.964 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.94 | 0.540 | 0.527 | 0.474 | 0.475 | 0.415 | 0.379 | 0.278 | 0.148 | 0.078 | 0.050 | 0.349 |
| 4.60 | 0.530 | 0.515 | 0.466 | 0.451 | 0.405 | 0.353 | 0.271 | 0.168 | 0.087 | 0.054 | 0.341 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.21 | 5.25 | 4.94 | 4.38 | 3.94 | 3.78 | 3.50 | 3.08 | 2.80 | 5.19 | 4.67 | 4.38 | 4.12 | 4.62 |
| 4.92 | 5.71 | 5.35 | 4.94 | 4.64 | 4.38 | 4.18 | 4.00 | 3.68 | 5.75 | 5.49 | 5.00 | 4.69 | 5.45 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525050
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m): 999
SOLIDS VOLUME FRACTION: 0.00

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.37 | 4.82 | 4.41 | 4.06 | 3.76 | 3.28 | 2.93 | 2.56 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0647 | 0.0529 | 0.0450 | 0.0385 | 0.0333 | 0.0259 | 0.0211 | 0.0163 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | --- |

INT = intermittent deposit. STA = stationary deposit.

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525051
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1247
SOLIDS VOLUME FRACTION: 0.15

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.23 | 4.95 | 4.64 | 4.37 | 4.14 | 3.98 | 3.83 | 3.75 | 3.40 | 3.22 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0808 | 0.0754 | 0.0700 | 0.0654 | 0.0623 | 0.0607 | 0.0582 | 0.0594 | 0.0507 | 0.0481 |
| Deposit | --- | --- | --- | --- | INT | INT | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (μm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.009 | 0.045 | 0.178 | 0.382 | 0.539 | 0.674 | 0.727 | 0.771 | 0.853 | 0.949 | 0.985 | 1.000 |
| PSD # 2 | 0.018 | 0.077 | 0.218 | 0.423 | 0.587 | 0.697 | 0.750 | 0.794 | 0.890 | 0.964 | 0.991 | 1.000 |

PSD # 1 Head sample

PSD # 2 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.13 | 0.523 | 0.411 | 0.252 | 0.161 | 0.098 | 0.060 | 0.042 | 0.027 | 0.024 | 0.018 | 0.147 |
| 4.87 | 0.525 | 0.403 | 0.249 | 0.155 | 0.098 | 0.071 | 0.046 | 0.035 | 0.025 | 0.029 | 0.149 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.41 | 4.86 | 4.83 | 4.72 | 4.64 | 4.44 | 4.00 | 3.33 | 2.46 | 5.60 | 5.45 | 4.94 | 4.24 | 5.28 |
| 5.21 | 5.60 | 5.60 | 5.45 | 5.38 | 5.00 | 4.67 | 4.24 | 3.68 | 6.61 | 6.22 | 5.83 | 5.03 | 6.18 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525052
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1412
SOLIDS VOLUME FRACTION: 0.25

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.19 | 4.92 | 4.67 | 4.41 | 4.15 | 3.84 | 3.60 | 3.34 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0903 | 0.0859 | 0.0826 | 0.0758 | 0.0740 | 0.0735 | 0.0667 | 0.0694 |
| Deposit | --- | --- | --- | --- | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.036 | 0.109 | 0.268 | 0.468 | 0.631 | 0.743 | 0.794 | 0.833 | 0.907 | 0.975 | 0.997 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.13 | 0.562 | 0.522 | 0.402 | 0.321 | 0.255 | 0.183 | 0.117 | 0.071 | 0.056 | 0.043 | 0.249 |
| 4.83 | 0.545 | 0.501 | 0.396 | 0.310 | 0.233 | 0.181 | 0.128 | 0.082 | 0.066 | 0.054 | 0.245 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.41 | 5.00 | 4.91 | 4.69 | 4.52 | 4.24 | 3.84 | 3.11 | 2.19 | 5.75 | 5.35 | 4.67 | 4.18 | 5.06 |
| 5.16 | 5.60 | 5.53 | 5.42 | 5.19 | 4.91 | 4.62 | 4.08 | 3.54 | 6.56 | 6.09 | 5.56 | 5.00 | 5.87 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525053
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1577
SOLIDS VOLUME FRACTION: 0.35

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.26 | 4.92 | 4.67 | 4.39 | 4.13 | 3.86 | 3.72 | 3.54 | 3.34 | 3.16 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1022 | 0.0951 | 0.0891 | 0.0832 | 0.0796 | 0.0734 | 0.0696 | 0.0639 | 0.0725 | 0.0763 |
| Deposit | --- | --- | --- | --- | --- | --- | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.040 | 0.113 | 0.266 | 0.462 | 0.623 | 0.738 | 0.794 | 0.838 | 0.912 | 0.978 | 0.993 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.10 | 0.584 | 0.562 | 0.500 | 0.446 | 0.379 | 0.319 | 0.238 | 0.165 | 0.124 | 0.096 | 0.346 |
| 4.83 | 0.560 | 0.550 | 0.479 | 0.443 | 0.366 | 0.304 | 0.242 | 0.195 | 0.147 | 0.116 | 0.344 |
| 0.00 | 0.679 | 0.713 | 0.712 | 0.690 | 0.682 | 0.049 | 0.011 | 0.005 | 0.004 | 0.000 | 0.363 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.38 | 5.06 | 4.86 | 4.57 | 4.38 | 4.12 | 3.78 | 3.26 | 2.86 | 5.53 | 5.12 | 4.62 | 4.24 | 4.88 |
| 5.16 | 5.49 | 5.42 | 5.28 | 5.00 | 4.91 | 4.57 | 4.18 | 3.50 | 6.27 | 6.00 | 5.60 | 5.06 | 5.87 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525054
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 40
SOLIDS: 0x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 992
SLURRY DENSITY (kg/cu m):1572
SOLIDS VOLUME FRACTION: 0.35

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.26 | 4.93 | 4.69 | 4.40 | 4.10 | 3.59 | 3.86 | 3.58 | 3.42 | 3.21 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0979 | 0.0918 | 0.0881 | 0.0833 | 0.0797 | 0.0713 | 0.0748 | 0.0691 | 0.0861 | 0.0883 |
| Deposit | --- | --- | --- | --- | --- | INT | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.061 | 0.147 | 0.304 | 0.487 | 0.634 | 0.739 | 0.792 | 0.831 | 0.911 | 0.974 | 0.994 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.41 | 0.588 | 0.522 | 0.471 | 0.441 | 0.385 | 0.326 | 0.232 | 0.154 | 0.102 | 0.067 | 0.335 |
| 4.10 | 0.611 | 0.587 | 0.504 | 0.464 | 0.383 | 0.313 | 0.221 | 0.144 | 0.098 | 0.071 | 0.344 |
| 4.84 | 0.602 | 0.572 | 0.501 | 0.452 | 0.379 | 0.308 | 0.218 | 0.158 | 0.121 | 0.096 | 0.344 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.38 | 5.12 | 4.94 | 4.62 | 4.38 | 4.18 | 3.84 | 3.22 | 2.46 | 5.68 | 5.00 | 4.52 | 4.12 | 4.83 |
| 5.17 | 5.75 | 5.68 | 5.35 | 5.05 | 4.88 | 4.62 | 3.94 | 3.33 | 6.51 | 6.00 | 5.53 | 5.00 | 5.75 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525055
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 0x6 mm SILICA SAND
CARRIER: WATER AND 0.5% CLAY

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1577
SOLIDS VOLUME FRACTION: 0.35

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.18 | 4.89 | 4.61 | 4.33 | 4.04 | 3.75 | 3.50 | 3.26 | 3.04 |
|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0994 | 0.0923 | 0.0839 | 0.0781 | 0.0713 | 0.0646 | 0.0605 | 0.0578 | 0.0605 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | --- | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 841 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.068 | 0.157 | 0.308 | 0.481 | 0.621 | 0.729 | 0.785 | 0.825 | 0.907 | 0.974 | 0.996 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.09 | 0.573 | 0.538 | 0.453 | 0.409 | 0.349 | 0.310 | 0.270 | 0.226 | 0.203 | 0.167 | 0.349 |
| 4.82 | 0.559 | 0.531 | 0.449 | 0.384 | 0.334 | 0.302 | 0.263 | 0.238 | 0.212 | 0.174 | 0.343 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.37 | 4.62 | 4.57 | 4.40 | 4.24 | 4.24 | 3.94 | 3.41 | 2.69 | 5.45 | 5.06 | 4.77 | 4.38 | 5.12 |
| 5.15 | 5.35 | 5.25 | 5.09 | 5.00 | 4.86 | 4.62 | 4.33 | 3.78 | 6.13 | 6.00 | 5.64 | 5.19 | 6.00 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525060
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm and 0.1x0.3 mm SILICA SAND MIX
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m): 999
SOLIDS VOLUME FRACTION: 0.00

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.28 | 4.74 | 4.31 | 3.92 | 3.55 | 3.15 | 2.84 | 2.49 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0621 | 0.0506 | 0.0424 | 0.0355 | 0.0295 | 0.0236 | 0.0194 | 0.0152 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | --- |

INT = intermittent deposit. STA = stationary deposit.

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525061
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm and 0.1x0.3 mm SILICA SAND MIX
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1247
SOLIDS VOLUME FRACTION: 0.15

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.26 | 4.76 | 4.43 | 4.09 | 3.80 | 3.55 | 3.26 | 3.15 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0919 | 0.0812 | 0.0750 | 0.0691 | 0.0653 | 0.0607 | 0.0576 | 0.0532 |
| Deposit | --- | --- | --- | --- | --- | --- | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.008 | 0.081 | 0.294 | 0.486 | 0.510 | 0.512 | 0.514 | 0.543 | 0.707 | 0.897 | 0.971 | 1.000 |
| PSD # 2 | 0.063 | 0.220 | 0.477 | 0.600 | 0.625 | 0.628 | 0.634 | 0.662 | 0.803 | 0.937 | 0.984 | 1.000 |

PSD # 1 Head sample

PSD # 2 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.97 | 0.578 | 0.423 | 0.221 | 0.140 | 0.104 | 0.091 | 0.069 | 0.059 | 0.049 | 0.041 | 0.160 |
| 4.63 | 0.536 | 0.414 | 0.221 | 0.131 | 0.105 | 0.090 | 0.071 | 0.062 | 0.053 | 0.047 | 0.157 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.24 | 4.62 | 4.57 | 4.54 | 4.38 | 4.24 | 3.78 | 2.72 | 2.37 | 5.25 | 5.12 | 4.69 | 4.18 | 5.00 |
| 4.95 | 5.25 | 5.19 | 5.12 | 5.03 | 4.94 | 4.54 | 3.64 | 2.59 | 6.09 | 5.83 | 5.60 | 4.97 | 5.79 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525062
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm and 0.1x0.3 mm SILICA SAND MIX
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1412
SOLIDS VOLUME FRACTION: 0.25

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.24 | 4.80 | 4.43 | 4.11 | 3.78 | 3.51 | 3.27 | 3.04 | 2.89 | 2.78 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1080 | 0.0953 | 0.0895 | 0.0829 | 0.0781 | 0.0734 | 0.0703 | 0.0671 | 0.0665 | 0.0696 |
| Deposit | --- | --- | --- | --- | --- | INT | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (μm) | 74 | 149 | 210 | 297 | 420 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.100 | 0.274 | 0.501 | 0.606 | 0.629 | 0.632 | 0.639 | 0.672 | 0.812 | 0.930 | 0.976 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.94 | 0.584 | 0.511 | 0.386 | 0.278 | 0.204 | 0.182 | 0.148 | 0.125 | 0.115 | 0.094 | 0.253 |
| 4.68 | 0.549 | 0.483 | 0.363 | 0.281 | 0.213 | 0.172 | 0.155 | 0.130 | 0.117 | 0.100 | 0.248 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.21 | 4.67 | 4.62 | 4.44 | 4.38 | 4.31 | 3.73 | 2.50 | 2.01 | 5.25 | 5.09 | 4.52 | 4.12 | 4.83 |
| 5.00 | 5.35 | 5.25 | 5.12 | 5.06 | 4.94 | 4.62 | 3.84 | 2.95 | 6.09 | 5.83 | 5.35 | 4.94 | 5.79 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525063
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm and 0.1x0.3 mm SILICA SAND MIX
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1577
SOLIDS VOLUME FRACTION: 0.35

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.27 | 4.79 | 4.43 | 4.05 | 3.58 | 3.28 | 3.06 | 2.83 | 2.75 | 2.63 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1225 | 0.1115 | 0.1050 | 0.0926 | 0.0863 | 0.0807 | 0.0774 | 0.0756 | 0.0754 | 0.0879 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (μm) | 74 | 149 | 210 | 297 | 420 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.115 | 0.256 | 0.414 | 0.486 | 0.503 | 0.505 | 0.513 | 0.547 | 0.690 | 0.827 | 0.990 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.97 | 0.607 | 0.567 | 0.496 | 0.408 | 0.316 | 0.271 | 0.230 | 0.213 | 0.196 | 0.166 | 0.342 |
| 4.67 | 0.595 | 0.568 | 0.491 | 0.412 | 0.327 | 0.278 | 0.238 | 0.213 | 0.208 | 0.189 | 0.347 |
| 0.00 | 0.732 | 0.737 | 0.765 | 0.623 | 0.453 | 0.131 | 0.085 | 0.001 | 0.000 | 0.000 | 0.356 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.24 | 4.72 | 4.57 | 4.52 | 4.44 | 4.12 | 3.68 | 3.33 | 2.46 | 5.25 | 4.88 | 4.54 | 4.12 | 5.03 |
| 4.99 | 5.32 | 5.15 | 4.94 | 4.88 | 4.85 | 4.59 | 4.00 | 3.94 | 5.92 | 5.68 | 5.42 | 5.03 | 5.68 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525064
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 40
SOLIDS: 2x6 mm and 0.1x0.3 mm SILICA SAND MIX
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 992
SLURRY DENSITY (kg/cu m):1572
SOLIDS VOLUME FRACTION: 0.35

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.21 | 4.80 | 4.45 | 4.14 | 3.83 | 3.47 | 3.20 | 2.96 | 2.71 | 2.61 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1133 | 0.1054 | 0.0954 | 0.0913 | 0.0851 | 0.0791 | 0.0749 | 0.0726 | 0.0662 | 0.0719 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | --- | --- | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 149 | 210 | 297 | 420 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.265 | 0.438 | 0.584 | 0.645 | 0.660 | 0.662 | 0.669 | 0.700 | 0.827 | 0.945 | 0.985 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.94 | 0.619 | 0.557 | 0.464 | 0.369 | 0.309 | 0.269 | 0.233 | 0.212 | 0.196 | 0.173 | 0.334 |
| 4.64 | 0.617 | 0.574 | 0.457 | 0.366 | 0.304 | 0.267 | 0.247 | 0.226 | 0.200 | 0.178 | 0.337 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.21 | 4.67 | 4.62 | 4.59 | 4.44 | 4.38 | 3.68 | 2.75 | 1.87 | 5.15 | 4.94 | 4.62 | 3.94 | 5.00 |
| 4.96 | 5.45 | 5.32 | 5.25 | 5.22 | 5.19 | 4.52 | 3.18 | 2.15 | 5.92 | 5.68 | 5.45 | 4.62 | 5.71 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525070
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m): 999
SOLIDS VOLUME FRACTION: 0.00

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 5.33 | 4.95 | 4.42 | 4.07 | 3.67 | 3.21 | 2.94 | 2.60 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0630 | 0.0573 | 0.0448 | 0.0384 | 0.0314 | 0.0248 | 0.0209 | 0.0166 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | --- |

INT = intermittent deposit. STA = stationary deposit.

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: B525071
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1214
SOLIDS VOLUME FRACTION: 0.13

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.80 | 4.49 | 4.16 | 3.87 | 3.53 | 3.25 | 2.96 | 2.79 | 2.67 | 2.53 |
|---|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1231 | 0.1172 | 0.1105 | 0.1049 | 0.1004 | 0.0957 | 0.0908 | 0.0881 | 0.0861 | 0.0685 |
| Deposit | --- | --- | --- | --- | INT | INT | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.012 | 0.017 | 0.025 | 0.033 | 0.085 | 0.414 | 0.795 | 0.942 | 1.000 |

PSD # 1 Head sample

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.61 | 0.482 | 0.403 | 0.240 | 0.123 | 0.068 | 0.036 | 0.021 | 0.021 | 0.012 | 0.013 | 0.127 |
| 4.52 | 0.476 | 0.406 | 0.248 | 0.129 | 0.063 | 0.040 | 0.025 | 0.019 | 0.025 | 0.014 | 0.130 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.83 | 5.68 | 5.60 | 5.60 | 5.42 | 5.03 | 4.12 | 2.46 | 1.40 | 6.27 | 5.92 | 5.42 | 4.77 | 5.68 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525072
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1362
SOLIDS VOLUME FRACTION: 0.22

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 3.92 | 3.60 | 3.56 | 3.33 | 3.15 | 2.99 | 2.75 | 2.53 | 2.37 |
|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1542 | 0.1539 | 0.1488 | 0.1461 | 0.1439 | 0.1423 | 0.1414 | 0.1315 | 0.1197 |
| Deposit | --- | --- | --- | --- | --- | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.012 | 0.017 | 0.025 | 0.033 | 0.085 | 0.414 | 0.795 | 0.942 | 1.000 |

PSD # 1 Head sample

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.25 | 0.552 | 0.509 | 0.395 | 0.289 | 0.188 | 0.125 | 0.086 | 0.061 | 0.049 | 0.041 | 0.221 |
| 4.08 | 0.559 | 0.505 | 0.396 | 0.296 | 0.194 | 0.129 | 0.081 | 0.058 | 0.045 | 0.042 | 0.222 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.47 | 4.67 | 4.91 | 4.44 | 4.12 | 3.59 | 2.69 | 1.17 | 0.82 | 4.83 | 4.59 | 3.89 | 2.80 | 4.24 |
| 4.36 | 5.68 | 5.60 | 5.38 | 5.06 | 4.24 | 2.92 | 1.99 | 1.33 | 6.18 | 5.60 | 4.67 | 3.78 | 5.25 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525073
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 40
SOLIDS: 2x6 mm SILICA SAND
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 992
SLURRY DENSITY (kg/cu m):1357
SOLIDS VOLUME FRACTION: 0.22

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.34 | 3.98 | 3.70 | 3.44 | 3.17 | 2.87 | 2.76 | 2.68 | 2.55 |
|---|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1465 | 0.1401 | 0.1359 | 0.1290 | 0.1253 | 0.1207 | 0.1230 | 0.1132 | 0.1081 |
| Deposit | --- | --- | --- | --- | INT | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.012 | 0.017 | 0.025 | 0.033 | 0.085 | 0.414 | 0.795 | 0.942 | 1.000 |

PSD # 1 Head sample

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.21 | 0.570 | 0.511 | 0.391 | 0.279 | 0.176 | 0.119 | 0.083 | 0.063 | 0.061 | 0.039 | 0.219 |
| 3.96 | 0.575 | 0.505 | 0.403 | 0.289 | 0.182 | 0.120 | 0.087 | 0.074 | 0.064 | 0.061 | 0.226 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.23 | 5.38 | 5.25 | 5.22 | 4.88 | 4.12 | 2.86 | 1.67 | 0.97 | 5.92 | 5.45 | 4.83 | 3.54 | 5.12 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525074
DATE: MARCH 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 15
SOLIDS: 2x6 mm SILICA SAND
CARRIER: WATER AND 0.5% CLAY

SOLIDS DENSITY (kg/cu m): 2650
CARRIER DENSITY (kg/cu m): 999
SLURRY DENSITY (kg/cu m):1379
SOLIDS VOLUME FRACTION: 0.23

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.54 | 4.25 | 3.88 | 3.66 | 3.22 | 3.03 | 2.74 | 2.56 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.1432 | 0.1351 | 0.1279 | 0.1228 | 0.1157 | 0.1119 | 0.1104 | 0.0993 |
| Deposit | --- | --- | --- | --- | INT | INT | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 595 | 1190 | 1680 | 2380 | 3360 | 4760 | 9510 |
|---|---|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.034 | 0.039 | 0.047 | 0.055 | 0.105 | 0.427 | 0.800 | 0.943 | 1.000 |

PSD # 1 Head sample

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.32 | 0.591 | 0.530 | 0.397 | 0.276 | 0.188 | 0.126 | 0.098 | 0.080 | 0.068 | 0.061 | 0.230 |
| 4.35 | 0.562 | 0.515 | 0.404 | 0.289 | 0.187 | 0.127 | 0.100 | 0.083 | 0.082 | 0.065 | 0.231 |
| 0.00 | 0.676 | 0.688 | 0.637 | 0.193 | 0.095 | 0.091 | 0.086 | 0.071 | 0.065 | 0.018 | 0.246 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.65 | 5.60 | 5.68 | 5.53 | 5.38 | 4.88 | 3.89 | 2.15 | 1.23 | 6.18 | 5.92 | 5.25 | 4.12 | 5.60 |

# APPENDIX B: BEDDING DETECTOR OUTPUT

## ELECTRIC BEDDING PROBE PERFORMANCE

| VELOCITY (m/s) | PROBE OUTPUT RMS (vdc) |
|---|---|
| Run #8525031 | |
| 4.86 | 0.030 |
| 4.29 | 0.040 |
| 3.79 | 0.045 |
| 3.43 | 0.048 |
| 3.35 | 0.065 |
| 3.26 | 0.000 |
| Run #8525032 | |
| 4.10 | 0.043 |
| 3.86 | 0.045 |
| 3.50 | 0.041 |
| 3.33 | 0.408 |
| 3.19 | 0.001 |
| Run #8525033 | |
| 4.04 | 0.038 |
| 3.79 | 0.040 |
| 3.47 | 0.041 |
| 3.25 | 0.060 |
| 3.13 | 0.056 |
| 2.88 | 0.000 |
| Run #8525034 | |
| 5.23 | 0.004 |
| 4.43 | 0.005 |
| 3.86 | 0.009 |
| 3.26 | 0.013 |
| 2.90 | 0.002 |
| Run #8525035 | |
| 4.87 | 0.030 |
| 4.06 | 0.036 |
| 3.82 | 0.040 |
| 3.29 | 0.051 |
| 3.09 | 0.008 |
| Run #8525041 | |
| 5.22 | 0.009 |
| 4.60 | 0.013 |
| 3.96 | 0.018 |
| 3.30 | 0.035 |
| 2.92 | 0.001 |

| VELOCITY (m/s) | PROBE OUTPUT RMS (vdc) |
|---|---|
| Run #8525042 | |
| 5.22 | 0.008 |
| 4.60 | 0.010 |
| 3.96 | 0.019 |
| 3.26 | 0.029 |
| 2.88 | 0.002 |
| Run #8525043 | |
| 5.17 | 0.008 |
| 4.54 | 0.012 |
| 3.97 | 0.016 |
| 3.31 | 0.022 |
| 2.77 | 0.037 |
| 2.65 | 0.001 |
| Run #8525044 | |
| 5.26 | 0.002 |
| 4.43 | 0.003 |
| 3.69 | 0.004 |
| 2.76 | 0.010 |
| 1.94 | 0.000 |
| Run #8525051 | |
| 5.27 | 0.020 |
| 4.58 | 0.034 |
| 4.63 | 0.028 |
| 4.01 | 0.051 |
| 3.48 | 0.032 |
| 3.13 | 0.001 |
| Run #8525052 | |
| 5.28 | 0.017 |
| 4.78 | 0.023 |
| 4.29 | 0.036 |
| 3.81 | 0.043 |
| 3.28 | 0.002 |
| Run #8525053 | |
| 5.23 | 0.012 |
| 4.58 | 0.014 |
| 4.30 | 0.017 |
| 3.84 | 0.023 |
| 2.94 | 0.001 |

| VELOCITY (m/s) | PROBE OUTPUT RMS (vdc) |
|---|---|
| Run #8525054 | |
| 5.12 | 0.008 |
| 4.72 | 0.008 |
| 4.27 | 0.013 |
| 3.77 | 0.034 |
| 3.25 | 0.018 |
| 3.10 | 0.001 |
| Run #8525055 | |
| 5.18 | 0.008 |
| 4.73 | 0.008 |
| 4.24 | 0.010 |
| 3.79 | 0.012 |
| 3.05 | 0.019 |
| 2.94 | 0.020 |
| 2.84 | 0.002 |
| Run #8525061 | |
| 5.26 | 0.025 |
| 4.60 | 0.058 |
| 4.24 | 0.065 |
| 3.82 | 0.076 |
| 3.31 | 0.109 |
| 3.05 | 0.001 |
| Run #8525062 | |
| 5.24 | 0.028 |
| 4.61 | 0.046 |
| 4.30 | 0.042 |
| 3.77 | 0.063 |
| 3.32 | 0.073 |
| 2.82 | 0.001 |
| Run #8525063 | |
| 5.25 | 0.024 |
| 4.80 | 0.043 |
| 4.28 | 0.028 |
| 3.85 | 0.054 |
| 3.32 | 0.068 |
| 2.52 | 0.001 |
| Run #8525064 | |
| 5.05 | 0.027 |
| 4.71 | 0.025 |
| 4.28 | 0.032 |
| 3.82 | 0.033 |
| 3.24 | 0.039 |
| 2.63 | 0.000 |

| VELOCITY (m/s) | PROBE OUTPUT RMS (vdc) |
|---|---|
| Run #8525071 | |
| 4.68 | 0.025 |
| 3.99 | 0.033 |
| 3.10 | 0.071 |
| 2.71 | 0.097 |
| 2.33 | 0.000 |
| Run #8525072 | |
| 3.95 | 0.063 |
| 3.64 | 0.051 |
| 3.15 | 0.091 |
| 2.64 | 0.133 |
| 1.81 | 0.001 |
| Run #8525073 | |
| 4.36 | 0.021 |
| 3.88 | 0.027 |
| 3.36 | 0.042 |
| 2.96 | 0.064 |
| 2.53 | 0.077 |
| 1.71 | 0.006 |

# APPENDIX C: CARRIER FLUID VISCOSITY DATA

Brookfield viscometer dial deflections for carrier fluids (water and solids <0.074 mm).

| Run Number | RPM / T(°C) | 3 | 6 | 12 | 30 | 60 | 30 | 12 | 6 | 3 |
|---|---|---|---|---|---|---|---|---|---|---|
| 8525033 | 17 | | | | 8.5 | 16.1 | | | | |
| 8525041 | 15 | | | 2.6 | 6.0 | 13.0 | 6.4 | 2.7 | | |
| 8525042 | 15 | | | 2.7 | 6.9 | 14.7 | 6.8 | | | |
| 8525043 | 15 | | | 2.7 | 6.8 | 13.4 | 6.6 | | | |
| 8525045 | 40 | | | 2.1 | 5.0 | 9.7 | | | | |
| 8525053 | 15 | | | 6.2 | 11.3 | 19.7 | 10.6 | 5.3 | 3.1 | 1.3 |
| 8525054 | 40 | 3.1 | 4.6 | 6.3 | 10.0 | 17.1 | 9.6 | 4.8 | 3.0 | 1.4 |
| 8525062 | 15 | | 2.5 | 4.7 | 8.1 | 15.4 | 7.9 | 3.2 | 1.8 | 0.6 |
| 8525063 | 15 | | 4.7 | 8.0 | 13.7 | 22.5 | 13.8 | 8.0 | 5.5 | |
| 8525064 | 40 | 2.9 | 4.0 | 6.2 | 10.2 | 16.4 | 9.0 | 4.5 | | |
| 8525072 | 15 | | | 3.7 | 9.1 | 17.7 | 18.0 | 9.2 | 4.0 | 2.3 |
| Water | 20 | | | 2.2 | 5.5 | 11.5 | | | | |

Spindle diameter = 25.2 mm
Cup diameter = 27.6 mm

# APPENDIX D: DELIVERED CONCENTRATIONS

| Run Number | V (m/s) | $C_r$ | $C_{vd}$ (measured) | $C_{vd}$ (Model) |
|---|---|---|---|---|
| 8525031 | 3.94 | 0.152 | 0.107 | 0.118 |
| 8525031 | 4.37 | 0.153 | 0.115 | 0.122 |
| 8525032 | 3.90 | 0.246 | 0.199 | 0.197 |
| 8525032 | 4.38 | 0.249 | 0.202 | 0.205 |
| 8525033 | 3.90 | 0.294 | 0.250 | 0.242 |
| 8525033 | 4.34 | 0.294 | 0.256 | 0.248 |
| 8525034 | 3.92 | 0.305 | 0.277 | - |
| 8525034 | 4.35 | 0.306 | 0.289 | - |
| 8525035 | 3.95 | 0.302 | 0.258 | 0.242 |
| 8525035 | 4.38 | 0.301 | 0.259 | 0.248 |
| 8525041 | 3.94 | 0.162 | 0.137 | 0.144 |
| 8525041 | 4.68 | 0.155 | 0.138 | 0.140 |
| 8515042 | 3.95 | 0.248 | 0.221 | 0.223 |
| 8525042 | 4.65 | 0.243 | 0.227 | 0.225 |
| 8525043 | 3.98 | 0.339 | 0.329 | 0.312 |
| 8525043 | 4.68 | 0.335 | 0.326 | 0.313 |
| 8525044 | 3.11 | 0.345 | 0.342 | - |
| 8525044 | 4.70 | 0.327 | 0.326 | - |
| 8525045 | 3.94 | 0.349 | 0.324 | 0.316 |
| 8525045 | 4.60 | 0.341 | 0.324 | 0.314 |
| 8525051 | 4.13 | 0.147 | 0.114 | 0.128 |
| 8525051 | 4.87 | 0.149 | 0.121 | 0.132 |
| 8525052 | 4.13 | 0.249 | 0.210 | 0.219 |
| 8525052 | 4.87 | 0.245 | 0.218 | 0.220 |
| 8525053 | 4.10 | 0.346 | 0.319 | 0.313 |
| 8525053 | 4.87 | 0.344 | 0.326 | 0.317 |
| 8525054 | 4.10 | 0.344 | 0.311 | 0.307 |
| 8515054 | 4.84 | 0.344 | 0.317 | 0.313 |
| 8525055 | 4.09 | 0.349 | 0.331 | - |
| 8525055 | 4.82 | 0.343 | 0.328 | - |
| 8525061 | 3.97 | 0.160 | 0.124 | - |
| 8525061 | 4.63 | 0.157 | 0.123 | - |
| 8525062 | 3.94 | 0.253 | 0.218 | - |
| 8525062 | 4.68 | 0.248 | 0.224 | - |
| 8525063 | 3.97 | 0.342 | 0.318 | - |
| 8525063 | 4.67 | 0.347 | 0.331 | - |
| 8525064 | 3.94 | 0.334 | 0.302 | - |
| 8525064 | 4.64 | 0.337 | 0.307 | - |
| 8525071 | 3.61 | 0.127 | - | 0.050 |
| 8525071 | 4.52 | 0.130 | 0.084 | 0.069 |
| 8525072 | 3.25 | 0.221 | 0.159 | 0.087 |
| 8525072 | 4.08 | 0.222 | 0.165 | 0.118 |
| 8525073 | 3.21 | 0.219 | - | 0.077 |
| 8525073 | 3.96 | 0.226 | 0.166 | 0.111 |
| 8525074 | 3.32 | 0.230 | - | - |
| 8525074 | 4.35 | 0.231 | 0.180 | - |

# APPENDIX E: PARTICLE DRAG COEFFICIENT DATA

Particle drag coefficients for silica sand

| d(mm) | $Re_p$ | $C_D$ |
|---|---|---|
| 0.254 | 9.95 | 4.05 |
| 0.359 | 21.3 | 2.51 |
| 0.508 | 40.9 | 1.92 |
| 0.718 | 81.2 | 1.38 |
| 1.02 | 139 | 1.30 |
| 1.02 | 158 | 1.03 |
| 1.44 | 260 | 1.05 |
| 2.03 | 430 | 1.09 |
| 2.87 | 711 | 1.12 |
| 4.06 | 1270 | 1.00 |
| 5.75 | 1990 | 1.15 |

## APPENDIX F: TWO-LAYER MODEL

The model employs mass balance and force balance relationships for the flow depicted schematically in Figure 20. The hypothetical horizontal interface separates the contact particle free upper layer from the lower layer of concentration $C_2$. The mass balance for the total slurry is

$$A\,V = A_1\,V_1 + A_2\,V_2 \qquad (1)$$

Force balances can be written for each layer and these are coupled through the stress on the interface. Assuming steady flow:

$$I\,\rho_f\,g = (\tau_1\,S_1 + \tau_{12}\,S_{12}) / A_1 \qquad (2)$$

$$I\,\rho_f\,g = (\tau_2\,S_2 - \tau_{12}\,S_{12}) / A_2 \qquad (3)$$

The first step in using the model to calculate headlosses is to select a value for the lower layer concentration $C_2$. In this study, $C_2$ was set equal to 0.6 which is close to the experimentally determined value for concentration in a stationary deposit. (See Appendix A - gamma ray gauge concentration profiles for V = 0.0 m/s, Run #'s 8525033, 8525043, 8525053, 8525063 and 8525074.)

The next step is to obtain a value for $C_c$, the total contact load. The correlation described in Section 3.2 may be used. Once a value is determined for $C_c$, the suspended load $C_1$ can be calculated:

$$C_1 = C_T - C_c$$

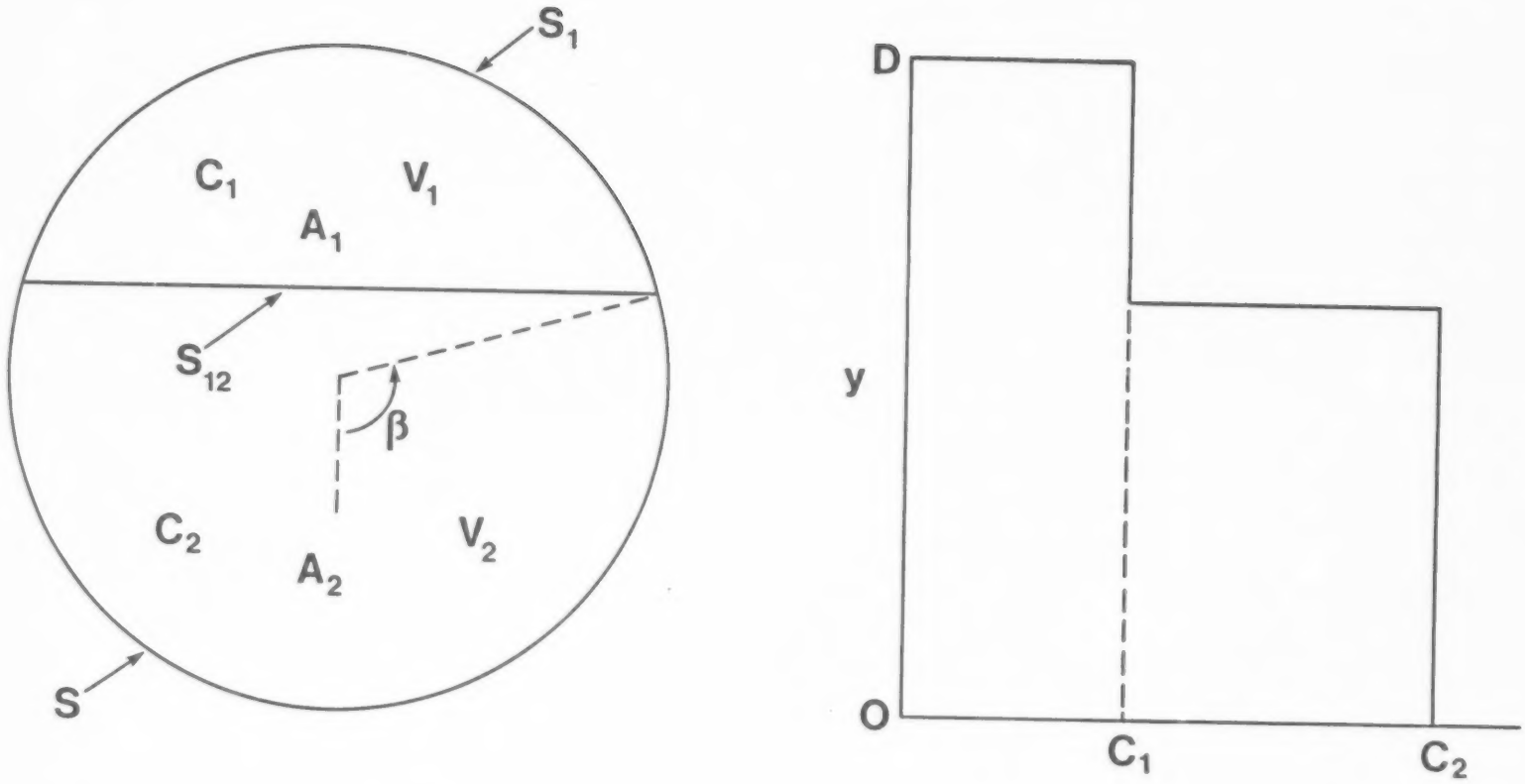


Fig.20 - Two layer model for pipeline flow of slurries

Once $C_1$ and $C_c$ are fixed, the area $A_2$ can be calculated:

$$A_2 = A\ C_c \ / \ (C_1 - C_2)$$

Knowing $A_2$, the angle $\beta$ is determined iteratively:

$$A_2 = D^2\ (\beta - \sin\beta \cos\beta) \ / \ 4$$

From geometry,

$$A_1 = A - A_2$$

$$S_1 = D\ (\pi - \beta)$$

$$S_2 = D\ \beta$$

$$S_{12} = D \sin\beta$$

Equations 1, 2 and 3 are solved iteratively for the unknown variables $V_1$, $V_2$ and i. First, a value is selected for $V_1$. Selection of the correct value for $V_1$ will result in a headloss, i from Equation 2 matching the headloss calculated by using Equation 3. As a starting point for the iteration, let $V_1 = V$. $V_2$ is then calculated from Equation 1:

$$V_2 = (A\ V - A_1\ V_1) \ / \ A_2$$

The stresses are calculated as follows:

$$\tau_1 = f_1\ V_1\ |V_1|\ \rho_1 \ / \ 2$$

$$f_1 = f_1\ [Re_1,\ \varepsilon/D]$$

Churchill's equation (Churchill, S.W., "Friction-factor equation spans all fluid-flow regimes", Chemical Engineering, Nov. 7, 1977, p91-91.) may be used to calculate $f_1$:

$$f_1 = 2\ [(8 \ / \ Re_1)^{12} + (a + b)^{-3/2}]^{1/12}$$

$$a = \{-2.457 \ln [(7 \ / \ Re_1)^{0.9} + 0.27\ \varepsilon \ / \ D]\}^{16}$$

$$b = (37530 \ / \ Re_1)^{16}$$

Also,

$$Re_1 = \rho_1 D V / \mu_1$$

$$\rho_1 = \rho_s C_1 + \rho_f (1 - C_1)$$

$$\mu_f = \mu_1 [\mu_f, C_1]$$

Setting $\mu_1 = \mu_f$ gave satisfactory results in this study. However, a concentration dependent viscosity function may be required for slurries with very high solids fractions.

Stress $\tau_{12}$ depends on the particle diameter and the difference in velocity between the layers:

$$\tau_{12} = f_{12} (V_1 - V_2) |V_1 - V_2| \rho_1 / 2$$

According to Wilson, $f_{12}$ is given by the rough boundary relationship as

$$f_{12} = 2 / [3.36 + 4 \log_{10} (D / d_m)]_2$$

The particle diameter, $d_m$ was chosen such that the weight fraction of the particles with diameter less than $d_m$ would be $C_1/C_r$.

Stress $\tau_2$ includes two effects; fluid-wall friction in the lower layer and particle-wall sliding friction. Neglecting transmission of stress $\tau_{12}$ through the lower layer and considering the effects of buoyancy produced by suspended particles in the lower layer,

$$\tau_2 S_2 = f_2 V_2 |V_2| \rho_1 S_2 / 2 + (\rho_s - \rho_2) g D^2 \eta_s (C_2 - C_1) (\sin\beta - \beta \cos\beta) / 2$$

The density of the suspended mixture in the lower layer ,

$$\rho_2 = [C_1 \rho_s + (1 - C_2) \rho_f] / [1 - C_2 + C_1]$$

The friction factor, $f_2$ may be approximated using $f_1$.

The experimentally determined coefficients of kinematic friction were:

$n_s = 0.4$ for coal

$n_s = 0.5$ for sand

## APPENDIX G - CONCENTRATION PROBE PERFORMANCE

A concentration/velocity probe has been developed at the University of Saskatchewan Department of Chemical Engineering. The L-shaped probe is shown schematically in Figure 21. A measurement system which minimizes polarization and velocity-dependence effects was developed by Nasr-el-Din et al (Reference 11).

If a current source is applied between the field electrode and the wall of the probe, the potential between the sensor electrodes will be directly proportional to the resistance in the region between them. The well known relationship linking electrical resistivity of a mixture to the volumetric concentration (Perry, R.H. and C.H. Chilton: Chemical Engineers' Handbook, 5th Ed., New York, McGraw-Hill, 1973, p3-243.) may be used to determine solids concentrations from the sensor electrode potentials. The solids concentration is

$$c = 2\,m \,/\, (3 + 2\,m)$$

where

$$m = (e - e_o) \,/\, e_o$$

$e$ = the potential between the electrodes for slurry

$e_o$ = the potential for the carrier alone.

The same probe may be used to determine local particle velocities. A direct current is applied between the field

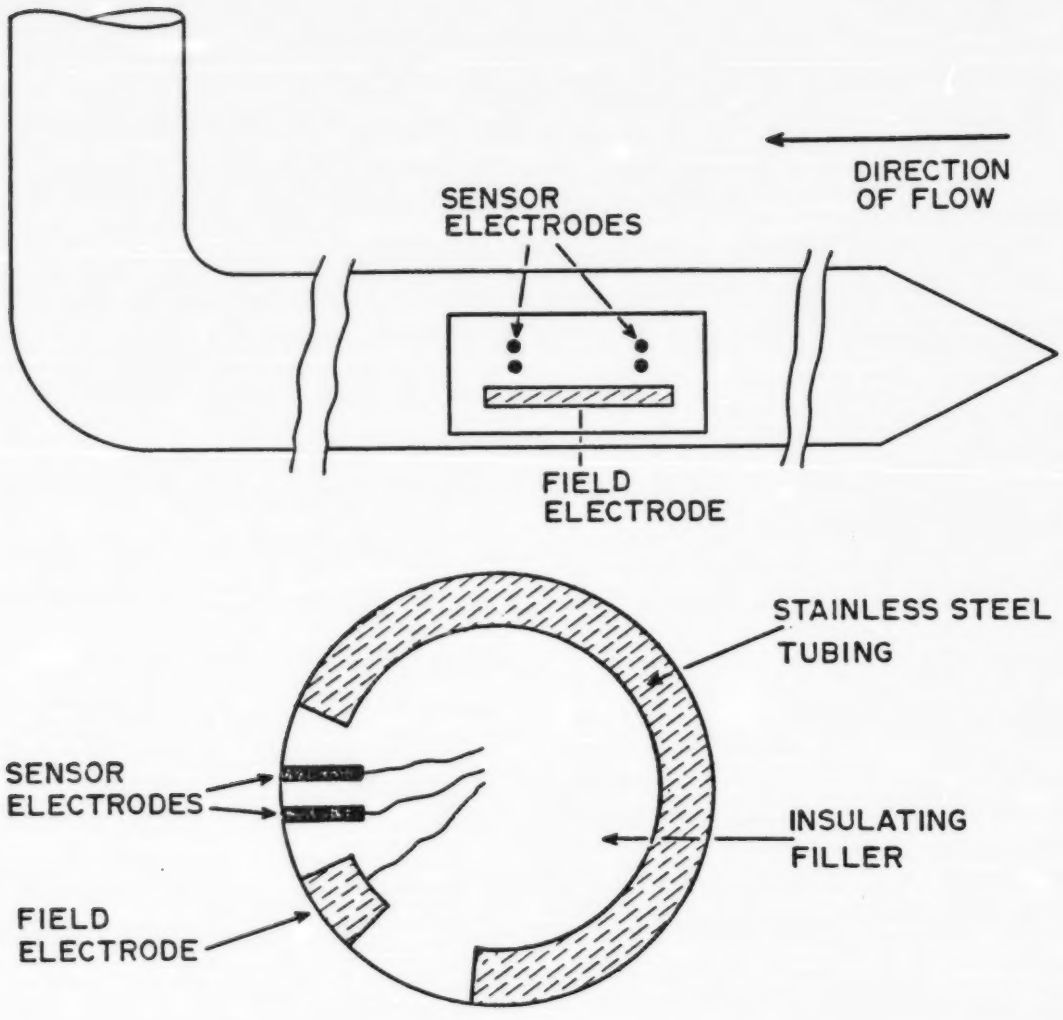


FIG. 21. CONCENTRATION/VELOCITY PROBE

electrode and the body of the probe. The potential difference between a pair of sensor electrodes fluctuates as particles pass by the electrodes. The cross-correlation principle is used to determine the travel time for particles passing between the axially displaced pairs of sensor electrodes. A Hewlett-Packard Model 3721A correlator is used to determine the transit times.

The probe was tested in a 495 mm diameter pipeline at the Saskatchewan Research Council to determine its performance for measuring concentration in full scale pipelines. Concentrations measured along the vertical axis of the pipeline are compared with chord-average gamma ray gauge results in Figure 22.

The good agreement between the two methods indicated that solids concentration was constant along a horizontal chord in the pipe. Measurements along the horizontal axis confirmed that there was no significant concentration variation along a horizontal plane in the full scale pipeline. In contrast, Nasr-el-Din et al found considerable variations in concentration along horizontal planes in a 50 mm pipe. They found that the solids concentration was lower near the pipe wall than at the centre of the pipe. The variation was particularly large for high concentrations and for coarse particles. The results of the two studies

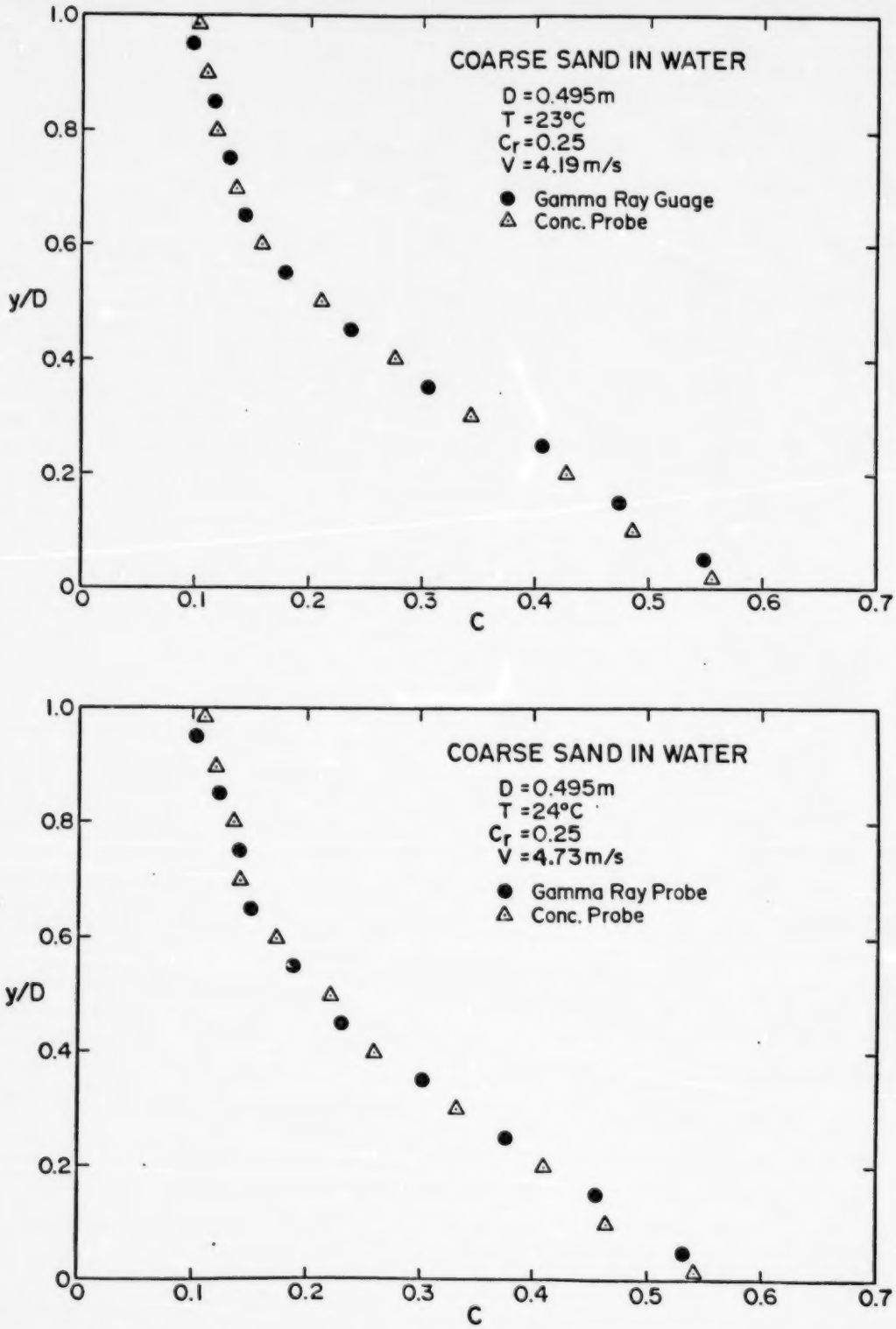


Figure 22. Concentration profiles for a coarse sand in water slurry flowing in a 495 mm pipe.

indicate that pipe size is also an important parameter affecting the horizontal concentration variation.

The concentration probe provides an excellent measure of local solids volume fraction without calibration. However, since the carrier fluid's electrical resistivity is normally very sensitive to temperature, the mixture temperature and the carrier's resistivity/temperature behavior must be known accurately.

# Volume

# 2

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# A STUDY OF FLOW CONDITIONS ARISING IN HORIZONTAL COARSE SLURRY SHORT DISTANCE PIPELINING PRACTICE PHASE II: COAL-SLURRY TESTS IN A 250 mm PIPELINE

FINAL
~~Interim~~ Report

by

R.G. Gillies, W.H.W. Husband
and M.H. Small

for

C.A. Shook Consulting Ltd.

41 pp

Publication R-833-3-C-86

August, 1986

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## SUMMARY

With growing interest in pipeline transportation of slurries of coarse coal, a reliable method is required to extend available data. The Canada Centre for Mineral and Energy Technology, Department of Energy, Mines and Resources Canada has provided funding to generate the data necessary to develop a suitable predictive method. The experimental portion of the program was conducted by Saskatchewan Research Council under sub-contract to C.A. Shook Consulting Limited.

Tests were conducted in a 250 mm diameter (nominal) horizontal pipeline test loop using coarse coal-in-water slurries and sand/gravel-in-water slurries. Pressure gradients, concentration profiles, particle velocity distributions and delivered mixture concentrations were determined as functions of slurry flowrate and pipeline in-situ concentration.

The results of the coarse coal-in-water slurry tests are reported here. The sand/gravel slurry test results and work on coarse-particle slurry flow modelling are reported under separate cover (Reference 1).

Phases III and IV of this study will assess the effects of pipeline diameter on the behaviour of coarse-particle slurries. Sand/gravel mixtures will be tested in a 100 mm pipeline in Phase III and in a 500 mm pipeline in Phase IV.

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# 1. INTRODUCTION

There have been substantial advances in understanding the flow behaviour of coarse-particle slurries in recent years. Models based upon rational consideration of the mechanisms of energy dissipation in the pipeline have replaced strictly empirical methods for predicting slurry pipeline performance. However, due to the complex nature of the flow of two-phase mixtures, the mechanistic models must contain some empirical terms. A dearth of suitable experimental test results often limit the useful range of these empirical terms.

One mechanistic approach is the two-layer model originally proposed by Wilson (Reference 2). One of the essential features of the model is the role played by particles which are too large and/or to dense to be suspended by fluid lift forces. These are the so-called contact load particles, which produce increased frictional energy consumption during pipeline flow.

The two-layer model has been shown to be successful for very coarse-particle flows. The model has not been as successful for the transition category between coarse-particle and fine-particle slurries. This failure is due to inadequate predictions of the contact load/suspended load ratio in the tentative expressions proposed by Wilson and co-workers (Reference 3). Many slurries of industrial importance, such as Canadian coarse coals and oil sand tailings, fall into this transition size.

In Phase I of this program, a systematic study of the behaviour of sand/gravel-in-water slurries was carried out using a 250 mm diameter pipeline. Sand/gravel slurries were selected because, unlike coal, the solids properties remain reasonably constant during recirculation in a

test loop. The behaviour of coarse coal-in-water slurries was examined in Phase II. The results were used to develop a new method for predicting the contact load for the two-layer model. The main purpose of the coal tests was to verify that the idealized sand/gravel tests were applicable to slurries of greater practical importance. The results of the sand/gravel slurry tests and the model development work were reported in Reference 1. The coal slurry test results are reported here.

## 2. EQUIPMENT AND PROCEDURES

### 2.1 Test loop

The pipelining tests were carried out in a 250 mm diameter (nominal) pipeline loop at the Saskatchewan Research Council (SRC) Slurry Pipeline Development Centre. The loop is shown schematically in Figure 1. A differential pressure transducer was used to measure headlosses over a 29 m long horizontal test section. The inside diameter of the test section was 263 mm. The test section was originally coated internally with epoxy resin to provide a constant (and low) pipe roughness factor. However, the epoxy coating had been worn away from the lower third of the test section, exposing the carbon steel pipe. Clear water headloss versus velocity measurements were made prior to and following the slurry tests to obtain accurate estimates of the pipe roughness. The clear water tests indicated an average pipe roughness $\varepsilon$ of 6 microns.

A rubber lined centrifugal pump with a 300 mm inlet and a 250 mm discharge was used to circulate the slurries. A 190 kW electric motor was used to power the pump. A variable speed fluid drive provided flow control. The slurry flowrate was measured using a magnetic flux flowmeter.

A chilled ethylene glycol/water mixture was circulated through the annulus of a pipe-over-pipe heat exchanger to maintain a constant slurry temperature. Temperature was controlled to within 1°C.

The slurry flow regime was determined by visual inspection through a transparent acrylic section of pipe and with a Snamprogetti detection probe (Reference 4). The probe was flush-mounted on the pipe wall. The probe detects fluctuations in slurry electrical resistance which result

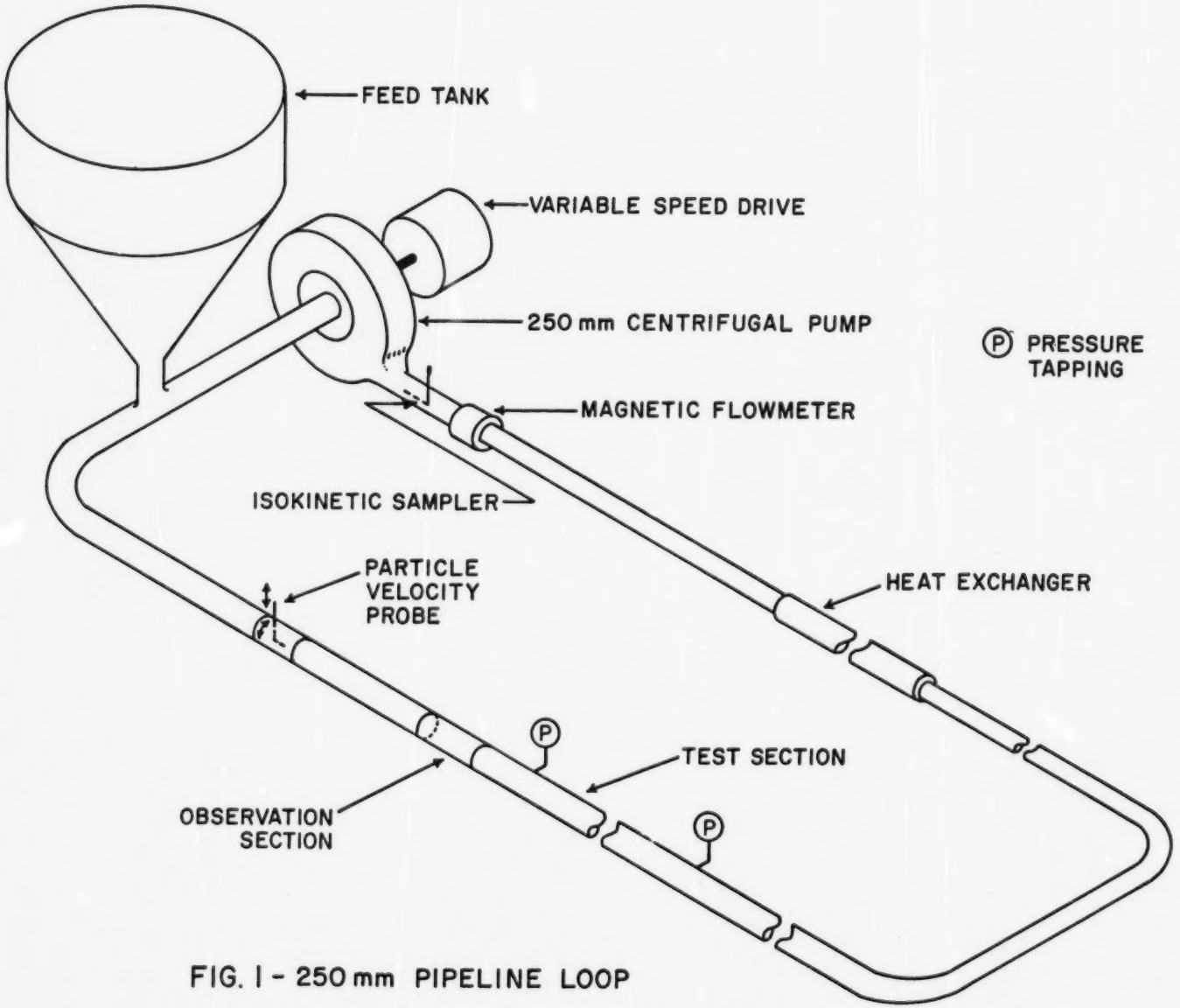



FIG. 1 - 250 mm PIPELINE LOOP

from the "macroturbulent" particle concentration fluctuations in the flow. These fluctuations increase in amplitude as the slurry velocity decreases and then disappear entirely if the probe becomes covered with a stationary deposit of particles.

Local particle velocities were determined by using a special probe, as described in the Phase I report.

A Hewlett-Packard 9825A computer and a NEFF 620 analogue-to-digital convertor measured and recorded all sensor readings. Instrument calibrations were performed prior to the slurry tests. Pressure transducers were calibrated using U-tube manometers. The magnetic flowmeter was calibrated against an orifice plate using water.

The coal sample was obtained from the Westar operation at Sparwood, British Columbia. The coal was a cleaned product and had a top size of 10 mm.

Each slurry test consisted of the following steps:

1. The pipeline loop was filled with water.
2. A pre-determined amount of coal was placed in the pipeline through the feed tank. The pipeline was operated at a flow velocity of approximately 2 m/s during the addition of the solids.
3. Headloss versus flowrate measurements were made starting at a high flowrate. The flowrate was reduced step-wise until a stationary deposit of solids was observed on the bottom of the pipe.
4. Samples for particle size analysis were removed as soon as the headloss determinations were completed.
5. The concentration profiles were determined at two velocities using a traversing chord-averaging gamma ray gauge. At the same time, local particle velocities were determined using an L-shaped probe.

The solids concentration was increased by adding coal to the previously tested slurry. The measurements described above were then repeated for the higher density slurry.

## 2.2 Sampling

The sampler shown in Figure 2 was used to withdraw samples at the discharge of the pump, where the solids were reasonably uniformly distributed over the cross-section of the pipe. The pump discharge samples were used to determine the particle size distributions of the solids contained in the mixtures delivered by the pipeline.

## 2.3 Concentration measurement

Since the pipeline test loop is horizontal and recirculating, the in-situ solids concentration is independent of slurry velocity. A traversing gamma ray gauge (Figure 3) was used to measure in-situ solids volume fraction in the 263 mm diameter test section. The gauge is described in the Phase I report. Chord-average values of in-situ solids concentration were determined and the average in-situ solids fraction was obtained by integrating the local values over the pipe cross-section.

The in-situ concentration is the pertinent variable for the modeler attempting to relate headlosses to the other slurry parameters. The delivered (or transport) concentration is of greater interest to the designer since it ultimately determines pipeline throughput. Delivered solids concentrations cannot be measured directly at the SRC facility. It is necessary to calculate the delivered concentration by integrating the product of local concentration measurements (gamma ray gauge

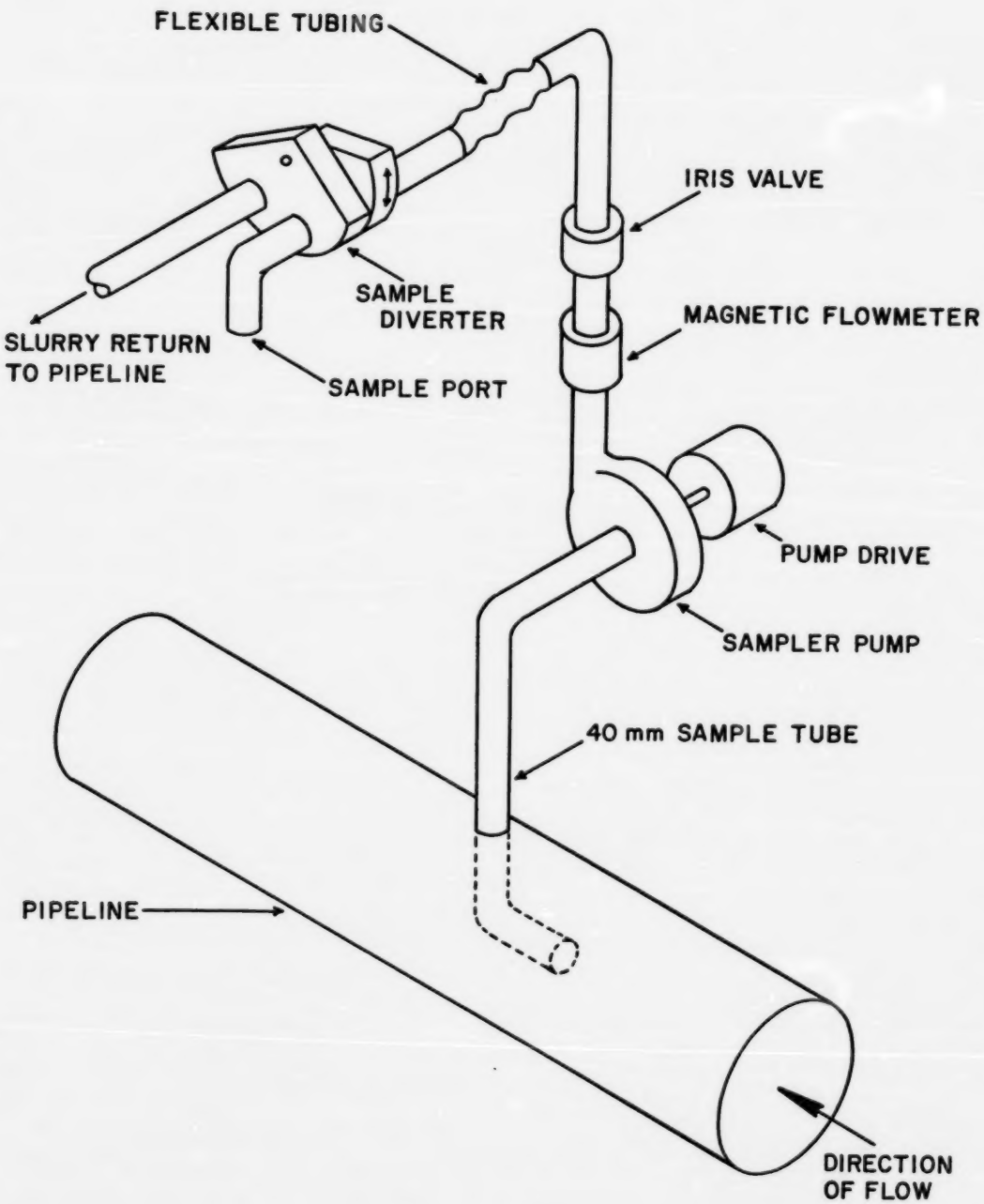



FIG. 2 - ISOKINETIC SAMPLER

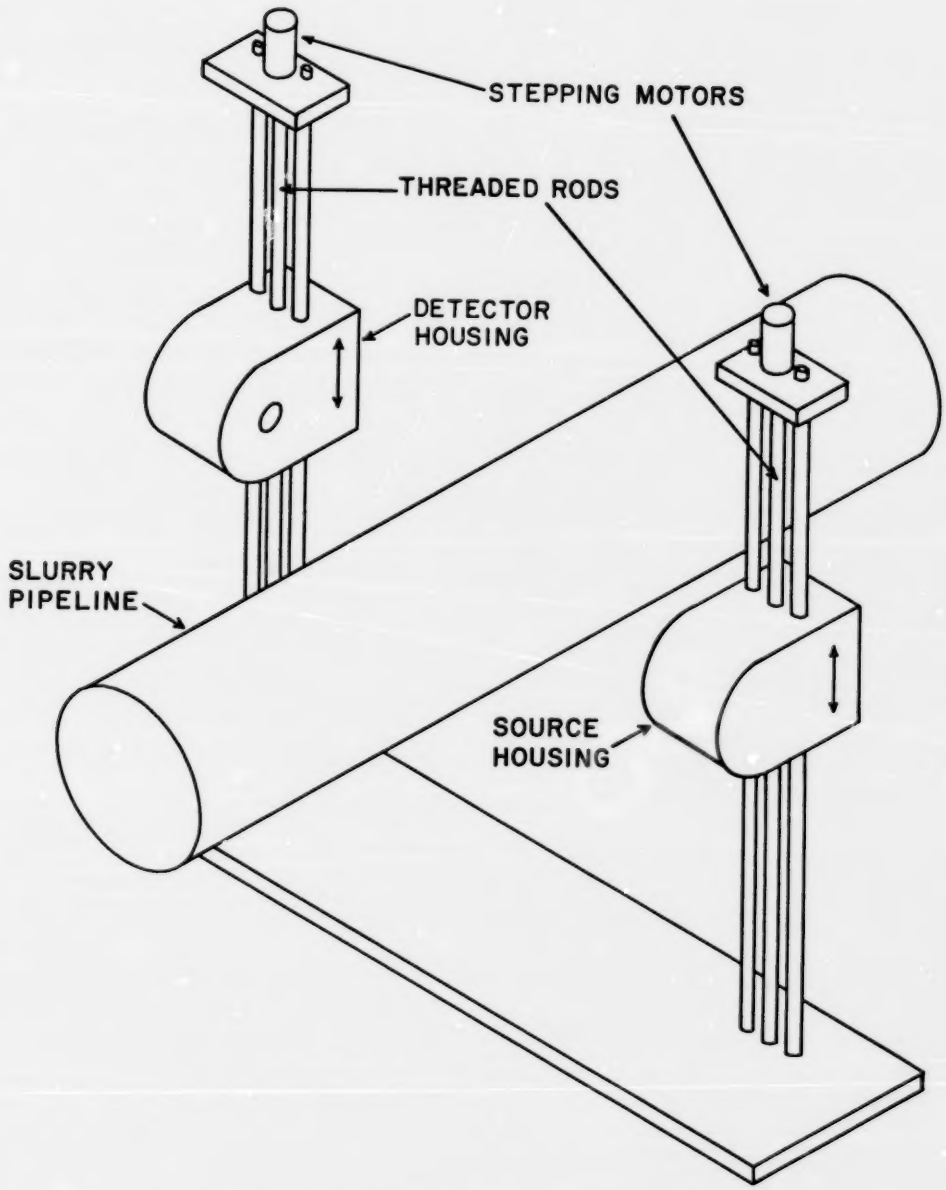


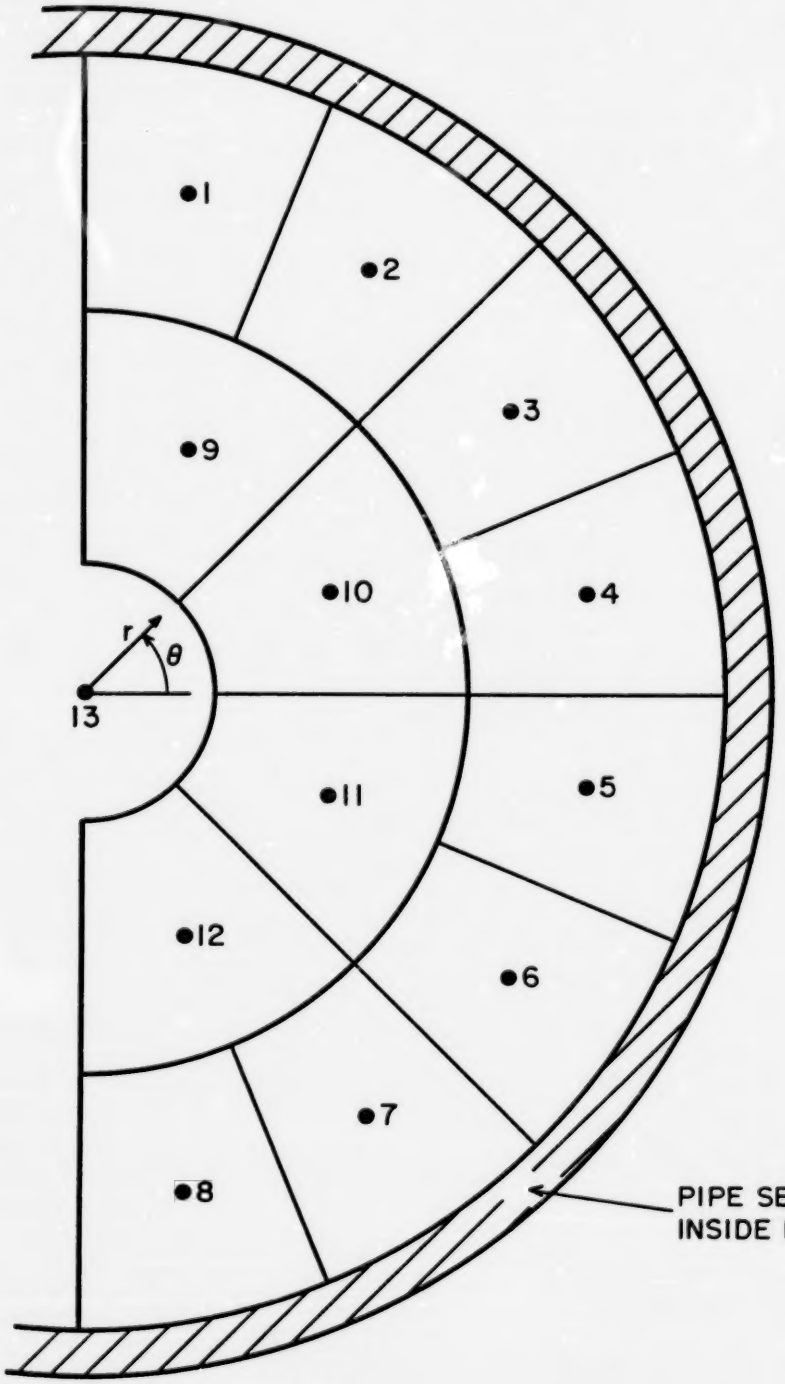

FIG. 3 - TRAVERSING GAMMA RAY GAUGE

results) and local particle velocity measurements. Particle velocity profiles were determined using a method described in the Phase I report. The pipe section could be rotated to allow sampling at any position. Figure 4 shows the locations of the sampling points used in the present study. It should be noted that the velocity probe was located in a pipe section with an inside diameter of 254.5 mm. This was somewhat smaller than the 263 mm test section.

## 2.4 Solids properties

Particle size distributions were determined using Tyler sieves. Slurry samples were air dried at 75•C for 24 hours and then weighed. The dried coal samples were wet screened using a 200 mesh (0.074 mm) sieve to remove the fines fraction. The coarse fraction was re-dried at 75•C and weighed to determine the amount of fines by difference. The distribution of the coarse fraction was determined by dry screening through a series of sieves and by weighing each fraction.

To accurately determine the in-situ solids concentration, one needs to know the equilibrium moisture and the "effective" density of the solids. Porous solids such as coals contain moisture in two forms; surface (or external) moisture and equilibrium (or internal) moisture. The surface moisture contributes volume to the carrier phase of the slurry while the internal moisture contributes to the solids fraction. The "effective" density is the density of the solid and its internal water at saturation conditions in the pipeline. To determine the "effective" density, a solid material must first be brought to an equilibrium moisture level. A modification of the ASTM procedure is used at the SRC facility. The coal sample is first crushed to minus 4




| POSITION | θ | r/R |
|---|---|---|
| 1 | 78.75° | 0.8 |
| 2 | 56.25° | 0.8 |
| 3 | 33.75° | 0.8 |
| 4 | 11.25° | 0.8 |
| 5 | -11.25° | 0.8 |
| 6 | -33.75° | 0.8 |
| 7 | -56.25° | 0.8 |
| 8 | -78.75° | 0.8 |
| 9 | 67.50° | 0.4 |
| 10 | 22.50° | 0.4 |
| 11 | -22.50° | 0.4 |
| 12 | -67.50° | 0.4 |
| 13 | — | 0.0 |

Fig. 4 - Sampling Positions for Particle Velocity Measurements

mm. It is then exposed to recirculating air at 92-95% relative humidity and 25°C in shallow, open trays. A period of several days may be required for the coal to reach equilibrium. The equilibrated condition is as close to the condition of saturation, which must exist in the pipeline, as can be reasonably achieved in the laboratory. Saturation moisture determinations were made by air drying the equilibrated samples at 105°C for 2 hours. Pycnometers were used to determine the "effective" density of the equilibrated coal particles. The Westar coal sample had a saturation moisture level of 1.8% (weight) and an "effective" density of 1374 $kg/m^3$.

## 2.5 Viscosity determinations

The carrier viscosity was measured using a Haake concentric cylinder viscometer. The viscometer has a stationary outer cylinder and a rotating inner cylinder. The minus 0.15 mm fraction of the slurry was considered to be the carrier for the viscosity tests. The slurry sample was withdrawn from the pipeline through the centre stream sampler. The plus 0.15 mm fraction was removed by screening. The minus 0.15 mm fraction was then concentrated by evaporating some of the water and tested at several solids concentrations using the Haake viscometer.

Mixtures of finely dispersed solids in water often show Bingham fluid properties. A Bingham fluid obeys the equation of state $\dot{\gamma} = (\tau - \tau_0)/\mu_p$. At low shear rates the yield stress $\tau_0$ exceeds the shear stress at some point in the annular space between the rotating spindle and the stationary cup of a concentric cylinder viscometer. As a result there is no flow in the outer portion of the space. A

non-linear relationship exists between shear stress at the surface of the rotor and shear rate:

$$\tau - \tau_0 (1 + \ln \tau/\tau_0) = 2 \mu_p \omega$$

where $\omega$ is the angular velocity of the rotor. At higher shear rates, the shear stress exceeds the yield stress throughout the annular space. For this situation the relationship between shear stress and shear rate is linear:

$$\tau (1 - R_1^2/R_2^2) - 2 \tau_0 \ln (R_2/R_1) = 2 \mu_p \omega$$

where $R_1$ is the radius of the rotor (18.4 mm) and $R_2$ is the radius of the cup (21.0 mm). The shear stress at the surface of the rotor is determined from the torque T and the effective height H of the rotor:

$$\tau = T / 2 \pi R_1^2 H$$

## 2.6 Kinematic friction

For slurries of coarse particles, headlosses exceed those of the clear fluid by an amount which depends, according to theoretical explanations, on the coefficient of friction between particles and pipe. In his description of the particle-wall friction process, Wilson (Reference 5) suggested that a tilting tube could be used to determine the coefficient without flow experiments. More recently, Eyler (Reference 6) has constructed and used an apparatus based upon the tilting tube principle. Eyler's design was closely followed in an apparatus constructed at SRC. Using the apparatus, it is possible to determine coefficients for particles submerged in water. The coefficient of kinematic friction was found to be $\eta_s$=0.4 for coal on carbon steel pipe.

## 3. RESULTS

The results of the pipeline tests are given in tabular form in Appendix A. The data in Appendix A include headlosses, particle size distributions, concentration profiles and velocity distributions.

The solids particle size distributions are shown in Figure 5. The Westar coal had a top size of 10 mm and a mass-average particle diameter ($d_{50}$) of 7 mm at the start of the pipeline tests. Pump discharge samples (taken immediately after the headloss determinations) contained high concentrations of fines. The minus 0.74 mm fraction increased from 4% to approximately 35% during the pipeline tests. The coal had been stored at SRC for 18 months prior to the pipeline tests and had become very friable.

The headlosses (Figure 6) for the Westar coal were very low in comparison with those for other coarse coals tested at the SRC facility (Reference 7). This was due to the high fines content and the low density of the Westar coal.

The solids deposition velocity was not strongly dependent on concentration. The Snamprogetti probe indicated that the onset of a stationary bed occurred at approximately 1.7 m/s for all three solids concentrations. Visual inspection confirmed the probe reading.

The concentration distributions are shown in Figures 7-9. At $C_T$=0.23, most of the solids travelled in the lower portion of the pipeline. Increasing the velocity from 2.3 to 3.0 m/s had very little effect on the concentration profiles. The distributions became more uniform as the total solids concentration increased.

Figures 10 and 11 show velocity distributions in a pipe section of 254.5 mm diameter. The velocity is reduced in the region of high solids

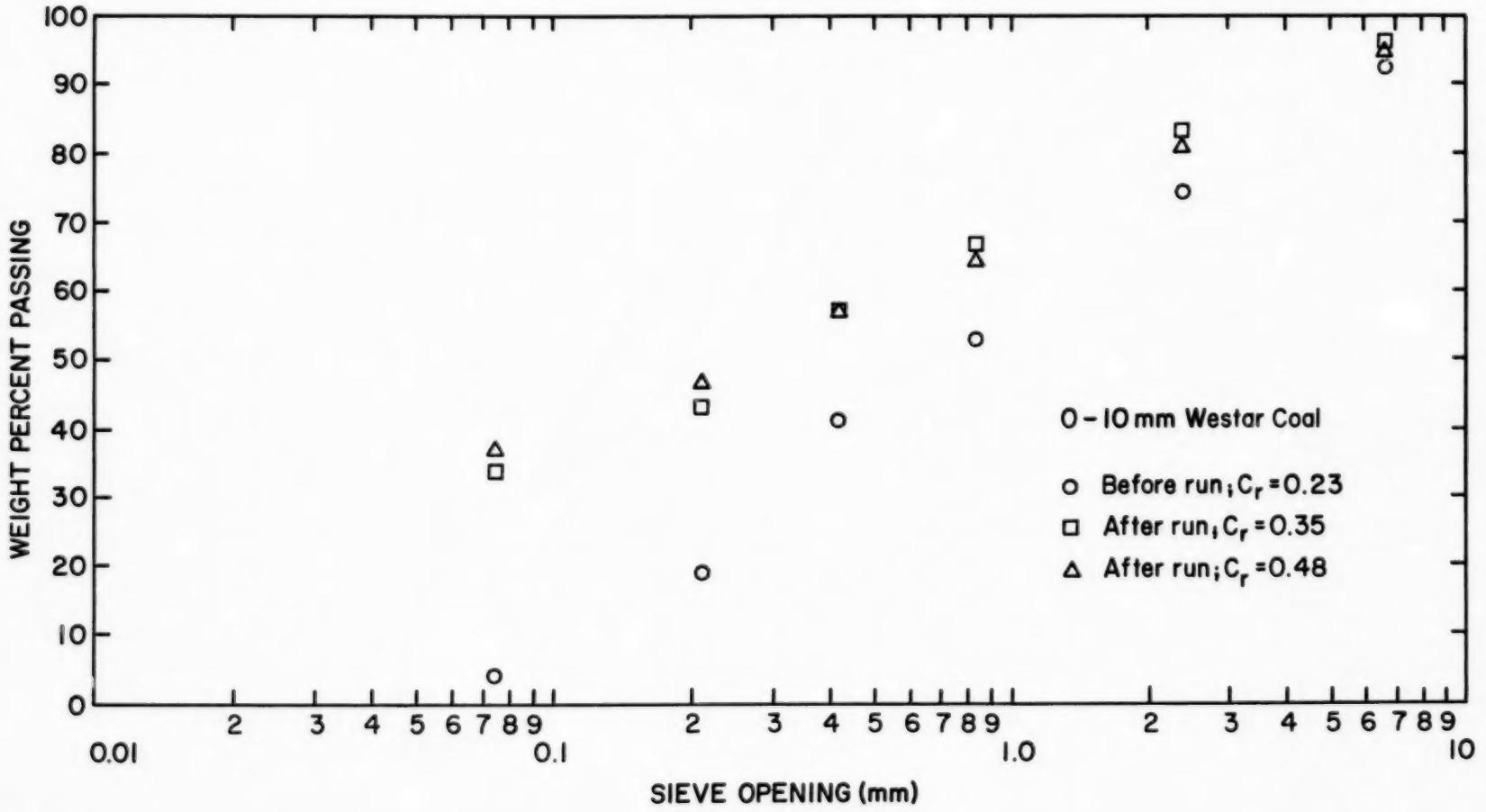



FIG. 5 - PARTICLE SIZE DISTRIBUTION FOR WESTAR COAL

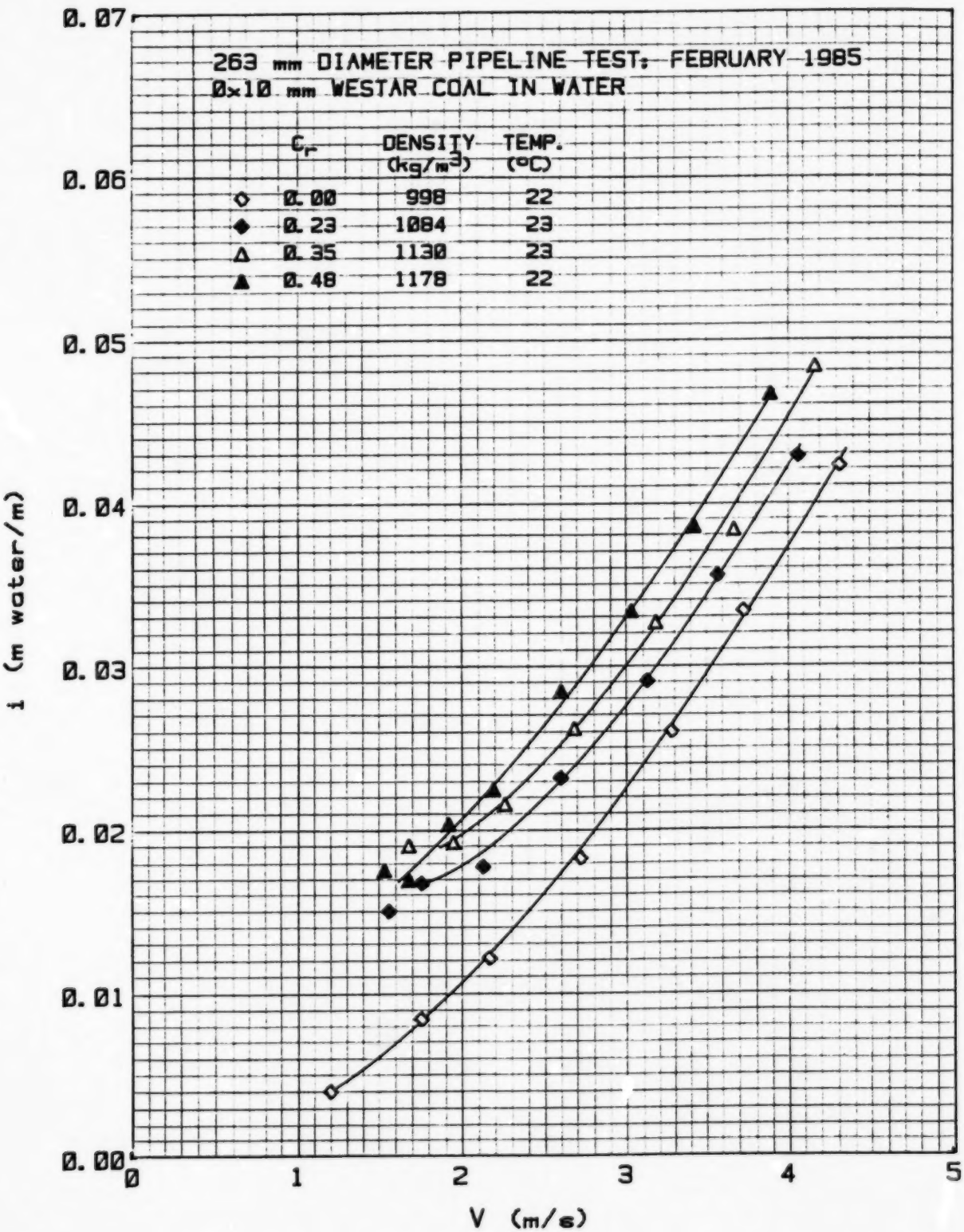



Figure 6. Headloss vs Velocity for Test Series # 852501

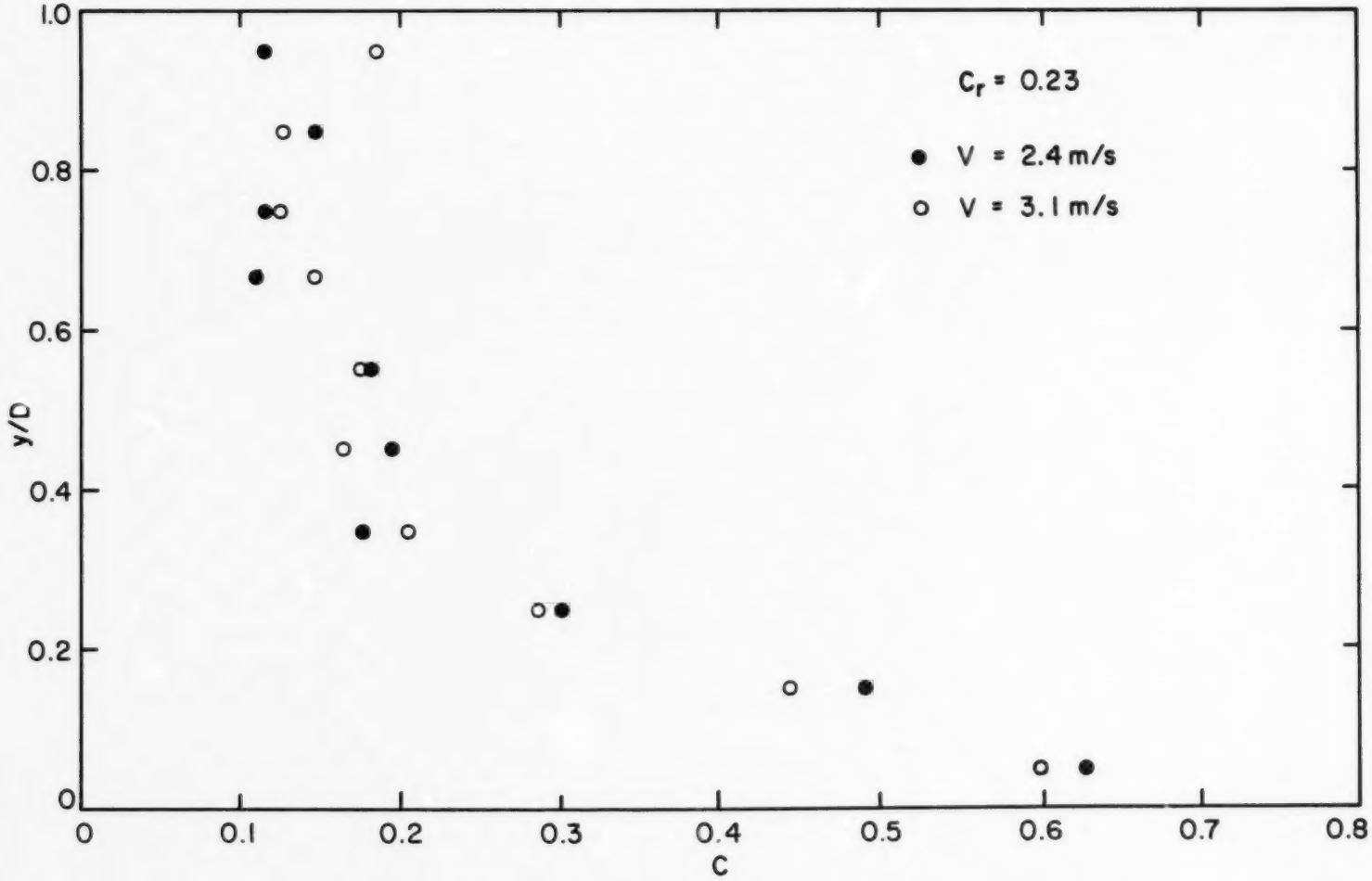



FIG. 7 - CONCENTRATION DISTRIBUTION OF SOLIDS

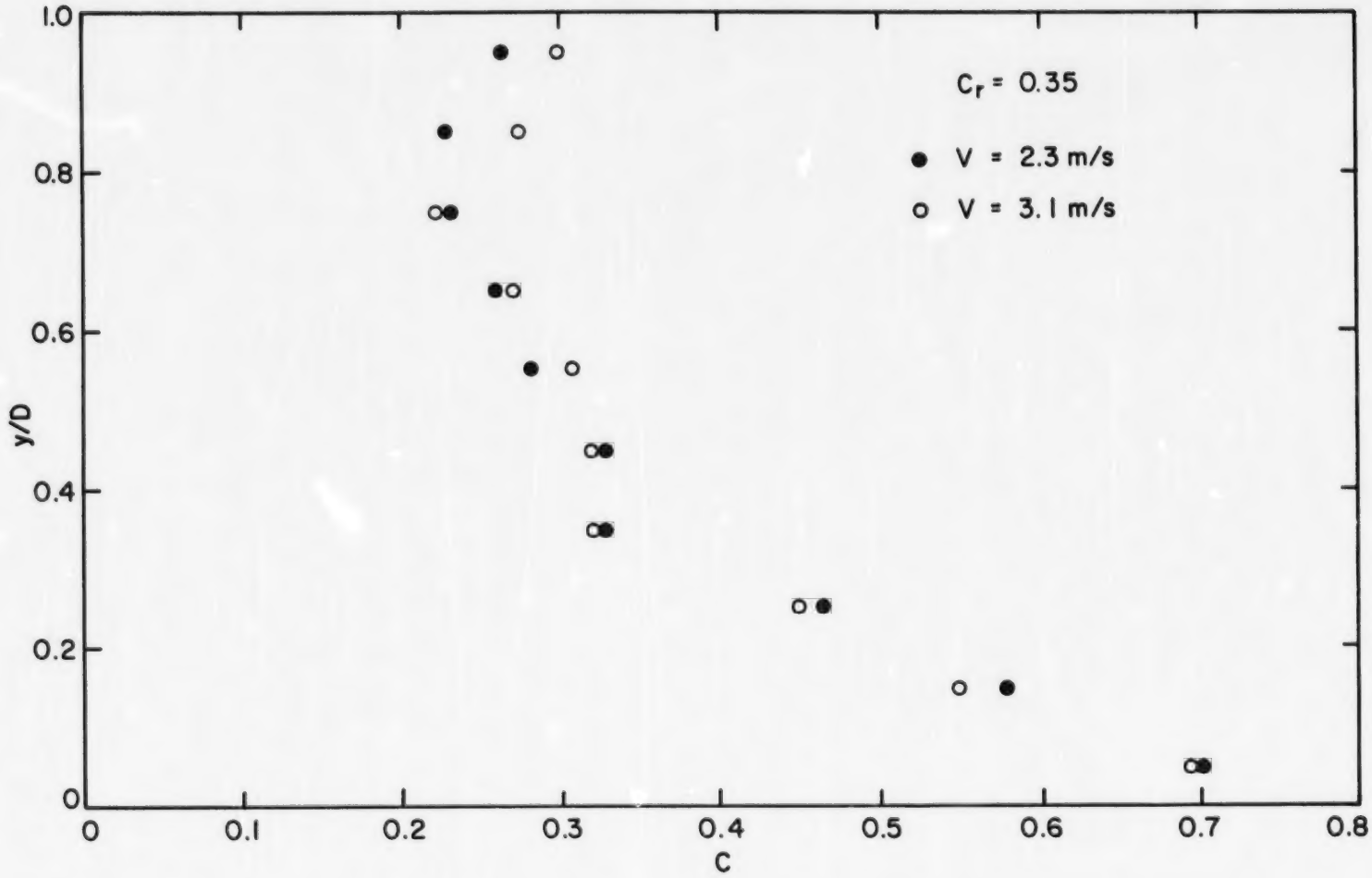



FIG. 8 - CONCENTRATION DISTRIBUTION OF SOLIDS

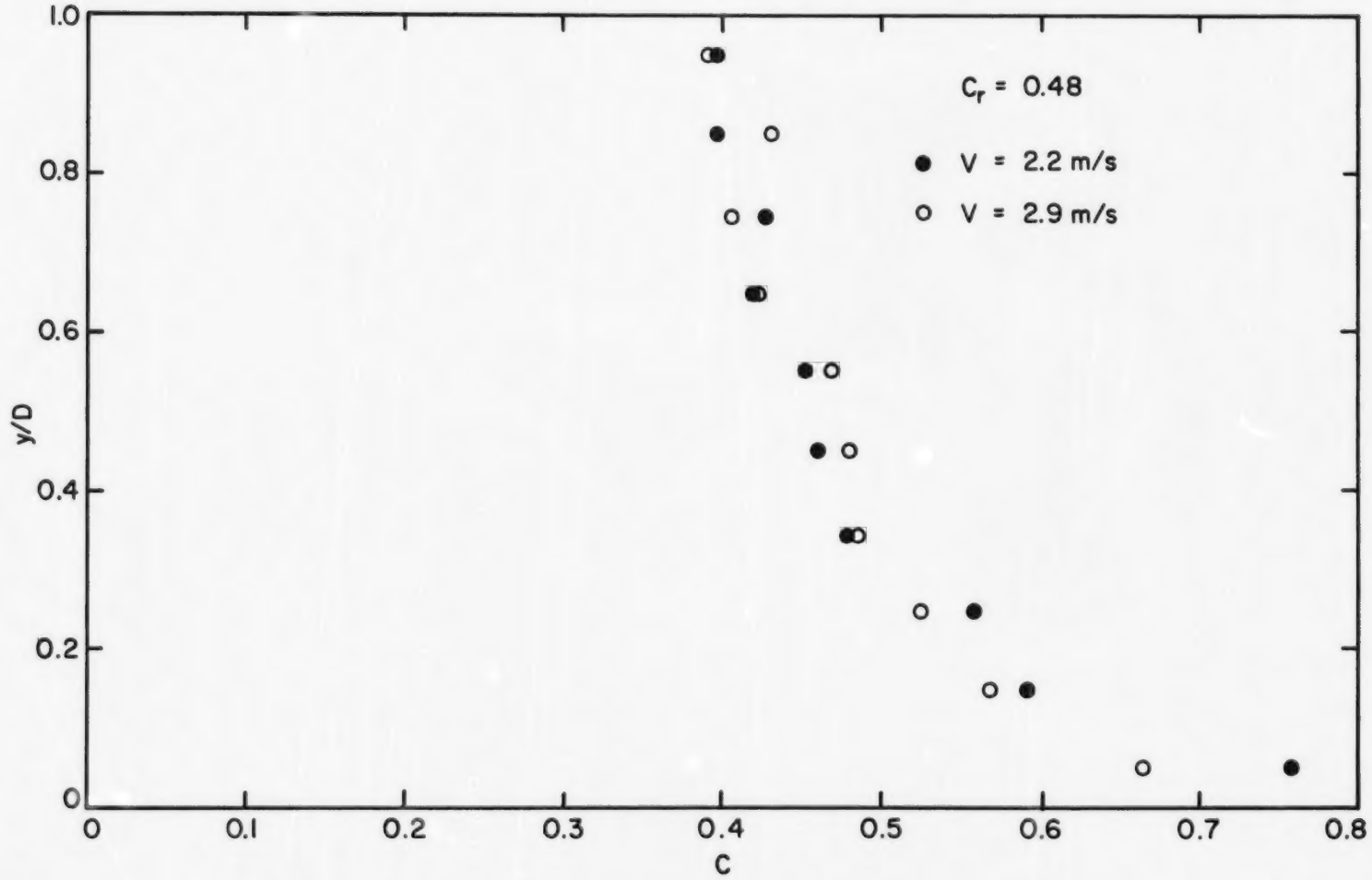



FIG. 9 - CONCENTRATION DISTRIBUTION OF SOLIDS

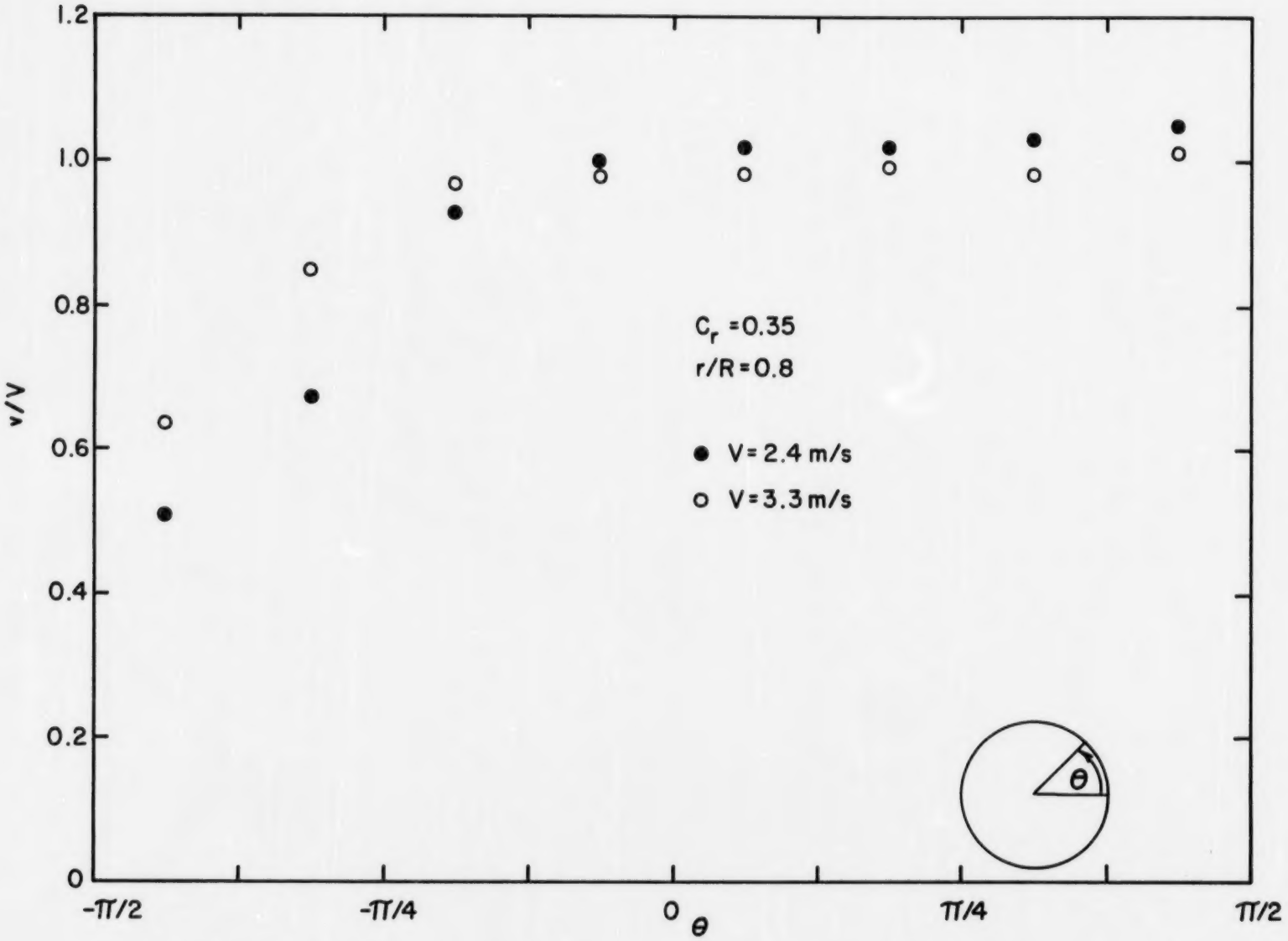



FIG. 10 - VELOCITY DISTRIBUTION OF SOLIDS AS A FUNCTION OF $\theta$

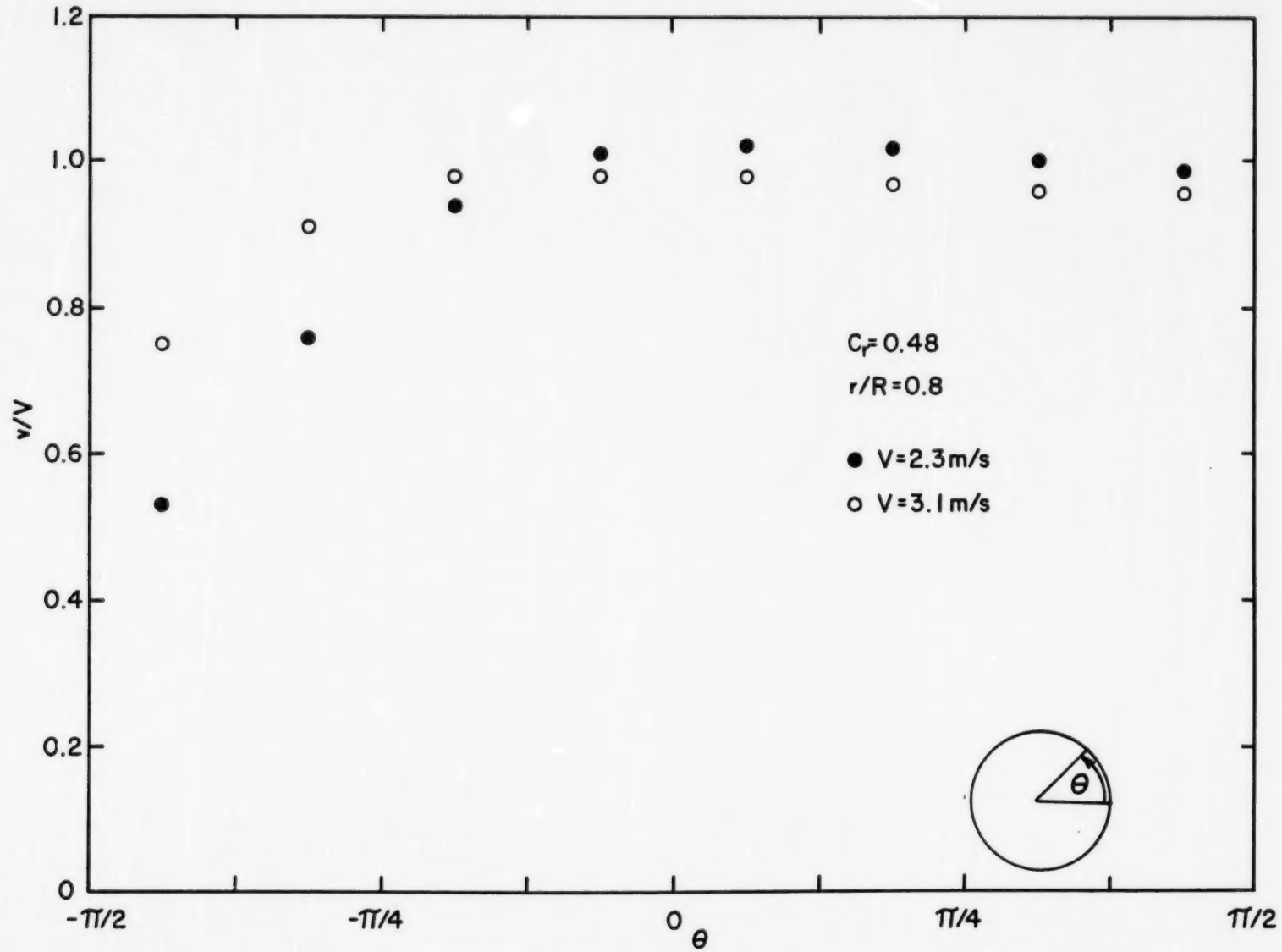



FIG. 11 - VELOCITY DISTRIBUTION OF SOLIDS AS A FUNCTION OF $\theta$

concentration near the bottom of the pipe. For the slurry with $C_r$=0.35 (Figure 10), the velocity profile became somewhat more uniform as the mean velocity increased from 2.4 to 3.3 m/s. Increasing the solids concentration to 48% by volume (Figure 11) also caused the velocity profile to become more uniform.

Delivered solids concentrations are reported in Table 1. The concentrated slurry in the lower portion of the pipe travels more slowly, on average, than the dilute slurry in the upper portion. As a result, the delivered mixture contains more carrier and less solids than the in-situ slurry in the horizontal line. The deviation between delivered and in-situ concentrations is greatest at low concentrations and low flowrates.

Table 1

A comparison of delivered and in-situ solids concentrations for minus 10 mm Westar coal/water slurries flowing in a horizontal 250 mm pipeline.

| Run # | V (m/s) | | $C_r$ | $C_{vd}$ |
|---|---|---|---|---|
| | MFM | Probe | | |
| 8525012 | 2.43 | 2.37 | 0.350 | 0.317 |
| 8525012 | 3.26 | 3.25 | 0.352 | 0.327 |
| 8525013 | 2.29 | 2.28 | 0.483 | 0.468 |
| 8525013 | 3.13 | 3.10 | 0.476 | 0.464 |

Table 1 also contains a comparison of average velocities determined using the magnetic flowmeter (MFM) and the probe. The good agreement verifies the excellent performance of the velocity probe.

Figure 12 shows the results of viscometer determinations on the minus 0.15 mm coal-in-water slurries. (The results are given in tabular form in Appendix B). The viscometer data fit the Bingham fluid model (solid lines) closely. In modelling the slurry flows, the plastic viscosity $\mu_p$ was used for the carrier fluid viscosity $\mu_f$.

A method for improving Wilson's two-layer model was suggested in Phase I. (The report on Phase I gives a detailed description of the version of the model used in the present study). An analysis using important dimensionless groups was chosen to find an improved method for predicting the contact load $C_c$ for slurries falling in the transition region between very coarse-particle slurries and fine-particle slurries. For very coarse slurries, the entire solids load is transmitted to the pipe wall, whereas, for fine-particle slurries, the solids are completely suspended by fluid lift forces. Experimental results from the present study and several previous studies were used to obtain the best fit equation for predicting $C_c$. It was found that the following correlation gave reasonable predictions for $C_c$ for a wide range of slurry pipelining conditions:

$$C_c = C_r \exp\left[k1\ Ar^{k2}\ (V^2/gd)^{k3}\ (d/D)^{k4}\ (\rho_s/\rho_f - 1)^{k5}\right]$$

where $C_r$ = total in-situ solids volume fraction

Ar = Archimedes number, $4\ g\ d^3\ \rho_f\ (\rho_s - \rho_f)\ /\ 3\ \mu_f^2$

g = acceleration of gravity

d = mass-average particle diameter

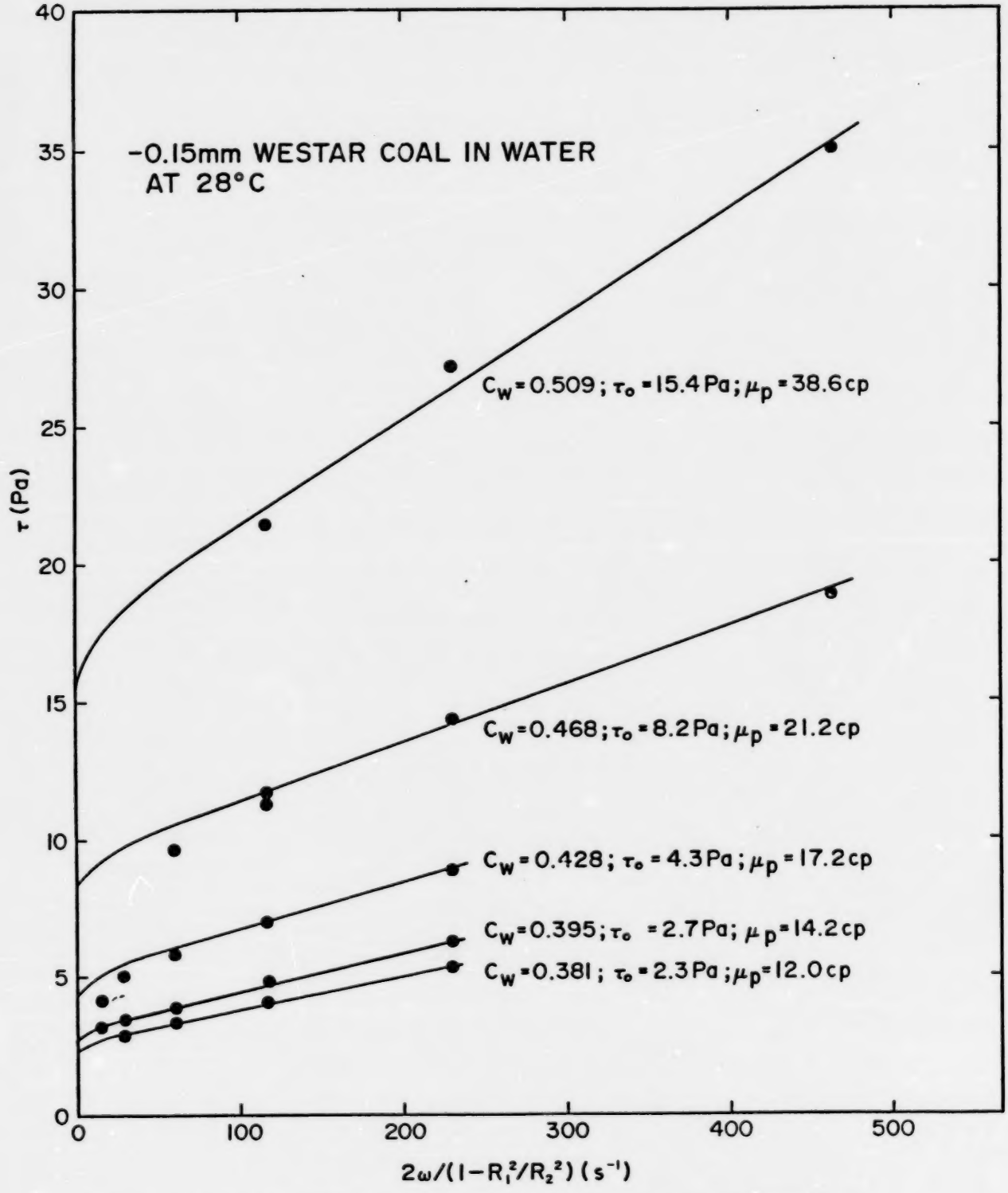



FIG. 12 - VISCOMETER DATA FOR WESTAR COAL SLURRIES.

D = pipe diameter

$\rho_f$ = carrier fluid density

$\rho_s$ = solids "effective" density

$\mu_f$ = carrier fluid viscosity

V = average slurry velocity

and the correlating constants (which should be considered tentative) are:

k1 = −0.124

k2 = −0.061

k3 = 0.028

k4 = −0.431

k5 = −0.272

Figure 13 shows the "goodness of fit" of the above correlating parameters. For modelling purposes, the minus 0.074 mm solids were considered to be a part of the carrier fluid. The fine solids contributed to both the viscosity and the density of the carrier. The plus 0.074 mm material was considered to be the solids portion of the slurry. The reasonable predictions show that the model is equally applicable to sand/gravel slurries and to coal slurries. In the absence of actual pipeline test data, the model should provide reasonably accurate headloss estimates for feasibility studies and for preliminary design. The model will also be useful for estimating the effects of changes in the operating conditions for existing slurry pipeline systems.

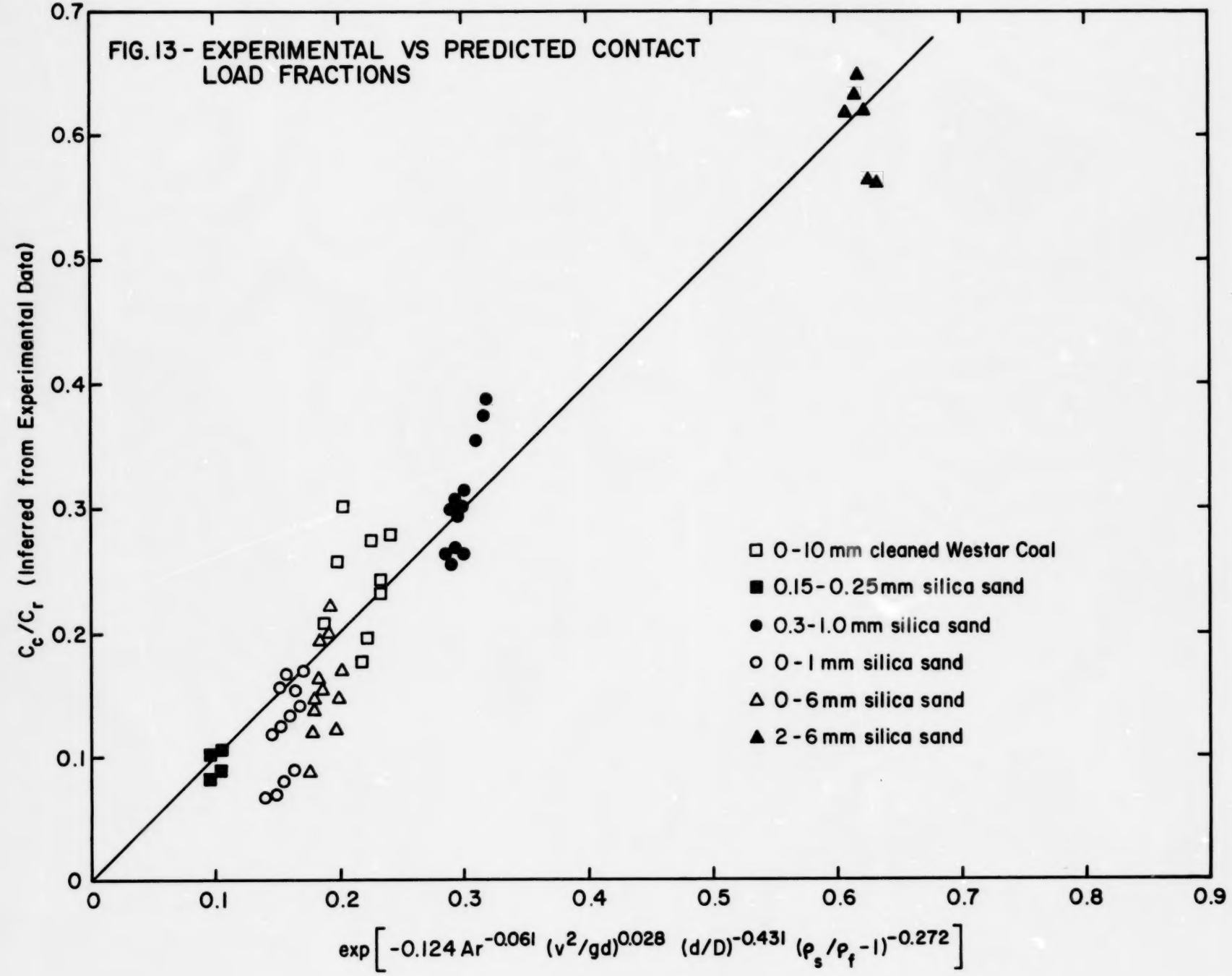


FIG. 13 - EXPERIMENTAL VS PREDICTED CONTACT LOAD FRACTIONS
$C_c/C_r$ (Inferred from Experimental Data)
$\exp\left[-0.124\,Ar^{-0.061}\,(v^2/gd)^{0.028}\,(d/D)^{-0.431}\,(\rho_s/\rho_f-1)^{-0.272}\right]$
0-10 mm cleaned Westar Coal
0.15-0.25mm silica sand
0.3-1.0 mm silica sand
0-1 mm silica sand
0-6mm silica sand
2-6 mm silica sand
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

## 4. CONCLUSIONS

The following conclusions were reached from the results of the first two phases of the study:

1. Idealized sand/gravel slurry data is useful for modelling coarse coal slurry flows.

2. The fluid viscosity, rather than slurry viscosity, appears to determine the contact load fraction of the mixture (at least for mixtures containing less than 35% solids by volume).

3. The in-situ volumetric concentration, rather than the delivered concentration, has been shown to be the appropriate parameter for use in the model.

4. For solids with a size distribution of moderate breadth, the mass mean particle diameter ($d_{50}$) is the appropriate parameter.

5. The tests have provided results for a range of particle sizes (to 6 mm for sand and to 10 mm for coal) in a 250 mm pipeline.

6. Existing data provide information on the effect of pipe diameter only for slurries with relatively fine particles (sand with a d50 of 0.18 mm).

7. The ratio of particle diameter to pipe diameter is of considerable importance in determining the contact load. This effect is much greater than previously indicated.

8. A tentative correlation for the prediction of contact load has been obtained using the data in items 5 and 6. This correlation is most reliable in the region covered by the present experiments. Further work, involving pipes of other sizes, is required to extend the range of applicability of the model.

9. In contrast with clay-water mixtures, clay-water-sand slurries exhibit complex rheology in some cases. Raw coal slurries (which sometimes contain substantial amounts of clay) may also exhibit complex rheology.

10. Even though the two-layer model is effective for predicting headlosses, measurements of local velocities and concentrations show that the model is based on a simplified picture of slurry flow in pipelines. The velocity profiles and concentration profiles measured in this study should provide a basis for understanding the mechanisms by which solids are suspended in horizontal pipelines.

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## 6. SYMBOLS

$Ar$ = Archimedes number, $4\ g\ d^3\ \rho_f\ (\rho_s-\rho_f)\ /\ 3\ \mu_f^2$

$C$ = solids volume fraction

$C_c$ = contact solids volume fraction

$C_r$ = in-situ solids volume fraction

$C_{vd}$ = solids volume fraction in delivered mixture

$C_w$ = in-situ solids weight fraction

$d$ = particle diameter

$D$ = pipe internal diameter

$g$ = gravitational acceleration

$H$ = effective height of viscometer rotor

$i$ = headloss gradient due to flow (m of water/m of pipe)

$r$ = radial distance

$R$ = radius of pipe

$R_1$ = radius of viscometer rotor

$R_2$ = radius of viscometer cup

$T$ = torque

$v$ = local velocity

$V$ = average velocity

$y$ = distance measured vertically from bottom of pipe

$\dot{\gamma}$ = shear rate

$\epsilon$ = effective roughness of pipe wall

$\eta_s$ = kinematic friction coefficient for particles and pipe

$\theta$ = angle defined in Figure 4

$\mu_f$ = dynamic viscosity of carrier fluid

$\mu_p$ = plastic viscosity (Bingham model)

$\rho_f$ = carrier fluid density

$\rho_s$ = solids "effective" density

$\tau$ = shear stress

$\tau_o$ = yield stress (Bingham model)

$\omega$ = angular velocity

# APPENDIX A

# PIPELINE DATA

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525010
DATE: FEBRUARY 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 22
SOLIDS: 0x10 mm WESTAR COAL
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 1374
CARRIER DENSITY (kg/cu m): 998
SLURRY DENSITY (kg/cu m): 998
SOLIDS VOLUME FRACTION: 0.00

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.32 | 3.74 | 3.29 | 2.73 | 2.18 | 1.77 | 1.21 |
|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0422 | 0.0333 | 0.0259 | 0.0182 | 0.0121 | 0.0084 | 0.0040 |
| Deposit | --- | --- | --- | --- | --- | --- | --- |

INT = intermittent deposit. STA = stationary deposit.

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525011
DATE: FEBRUARY 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 23
SOLIDS: 0x10 mm WESTAR COAL
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 1374
CARRIER DENSITY (kg/cu m): 998
SLURRY DENSITY (kg/cu m):1084
SOLIDS VOLUME FRACTION: 0.23

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.07 | 3.58 | 3.14 | 2.61 | 2.14 | 1.77 | 1.57 |
|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0428 | 0.0355 | 0.0290 | 0.0231 | 0.0177 | 0.0167 | 0.0150 |
| Deposit | --- | --- | --- | --- | --- | INT | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (μm) | 74 | 210 | 420 | 841 | 2380 | 6730 | 12700 |
|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.040 | 0.193 | 0.411 | 0.530 | 0.743 | 0.921 | 1.000 |

PSD # 1 Pump discharge sample (before run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.40 | 0.627 | 0.489 | 0.299 | 0.176 | 0.195 | 0.181 | 0.108 | 0.115 | 0.145 | 0.114 | 0.225 |
| 3.10 | 0.600 | 0.443 | 0.286 | 0.203 | 0.164 | 0.178 | 0.145 | 0.123 | 0.126 | 0.185 | 0.225 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525012
DATE: FEBRUARY 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 23
SOLIDS: 0x10 mm WESTAR COAL
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 1374
CARRIER DENSITY (kg/cu m): 998
SLURRY DENSITY (kg/cu m):1130
SOLIDS VOLUME FRACTION: 0.35

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 4.17 | 3.68 | 3.19 | 2.69 | 2.27 | 1.96 | 1.69 |
|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0483 | 0.0383 | 0.0326 | 0.0261 | 0.0215 | 0.0192 | 0.0190 |
| Deposit | --- | --- | --- | --- | --- | --- | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 420 | 841 | 2380 | 6730 | 12700 |
|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.335 | 0.431 | 0.572 | 0.665 | 0.834 | 0.956 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.30 | 0.702 | 0.580 | 0.464 | 0.327 | 0.328 | 0.283 | 0.257 | 0.231 | 0.227 | 0.264 | 0.350 |
| 3.10 | 0.696 | 0.548 | 0.450 | 0.321 | 0.318 | 0.307 | 0.270 | 0.223 | 0.274 | 0.297 | 0.352 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.43 | 2.49 | 2.45 | 2.42 | 2.42 | 2.37 | 2.20 | 1.59 | 1.20 | 2.85 | 2.85 | 2.74 | 2.52 | 2.94 |
| 3.26 | 3.27 | 3.19 | 3.22 | 3.17 | 3.18 | 3.14 | 2.75 | 2.07 | 3.72 | 3.73 | 3.69 | 3.50 | 3.93 |

SASKATCHEWAN RESEARCH COUNCIL SLURRY PIPELINE DEVELOPMENT CENTRE DATA

RUN #: 8525013
DATE: FEBRUARY 1985
PIPE DIAMETER (m): 0.263
TEMPERATURE (C): 22
SOLIDS: 0x10 mm WESTAR COAL
CARRIER: WATER

SOLIDS DENSITY (kg/cu m): 1374
CARRIER DENSITY (kg/cu m): 998
SLURRY DENSITY (kg/cu m): 1178
SOLIDS VOLUME FRACTION: 0.48

PIPELINE HEADLOSS (m water per m of pipe)

| V (m/s) | 3.90 | 3.43 | 3.04 | 2.61 | 2.20 | 1.93 | 1.69 | 1.54 |
|---|---|---|---|---|---|---|---|---|
| i (m/m) | 0.0466 | 0.0385 | 0.0333 | 0.0284 | 0.0224 | 0.0203 | 0.0169 | 0.0175 |
| Deposit | --- | --- | --- | --- | --- | --- | --- | STA |

INT = intermittent deposit. STA = stationary deposit.

PARTICLE SIZE DISTRIBUTION (Wt. fraction passing sieve)

| Size (Mm) | 74 | 210 | 420 | 841 | 2380 | 6730 | 12700 |
|---|---|---|---|---|---|---|---|
| PSD # 1 | 0.367 | 0.464 | 0.567 | 0.642 | 0.808 | 0.952 | 1.000 |

PSD # 1 Pump discharge sample (after run)

LOCAL CONCENTRATION (Horizontal chord average volume fraction)

| V(m/s) | y/D= 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.20 | 0.758 | 0.590 | 0.557 | 0.484 | 0.459 | 0.453 | 0.419 | 0.426 | 0.395 | 0.395 | 0.483 |
| 2.90 | 0.664 | 0.567 | 0.525 | 0.476 | 0.477 | 0.468 | 0.419 | 0.405 | 0.430 | 0.391 | 0.476 |

LOCAL VELOCITY (m/s)

| V(m/s) | POSITION= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.29 | 2.27 | 2.28 | 2.34 | 2.33 | 2.31 | 2.15 | 1.73 | 1.21 | 2.71 | 2.71 | 2.65 | 2.45 | 2.81 |
| 3.13 | 2.98 | 2.97 | 3.00 | 3.03 | 3.03 | 3.03 | 2.81 | 2.34 | 3.47 | 3.50 | 3.47 | 3.34 | 3.67 |

# APPENDIX B

## VISCOMETER DATA

Haake Viscometer Results for Minus 0.15 mm Westar Coal-in-Water Slurries at 28°C.

| Rotor RPM | Shear Stress (% of full scale) | $2\omega/(1-R_1^2/R_2^2)$ ($s^{-1}$) | $\tau$ (Pa) |
|---|---|---|---|
| | $C_w$ = 0.381 | | |
| 512 | 29.5 | 461.6 | 10.6 |
| 256 | 15 | 230.8 | 5.4 |
| 128 | 11.5 | 115.4 | 4.1 |
| 64 | 9.5 | 57.7 | 3.4 |
| 32 | 8 | 28.9 | 2.9 |
| 256 | 15 | 230.8 | 5.4 |
| 512 | 28 | 461.6 | 10.1 |
| | $C_w$ = 0.395 | | |
| 512 | 31.5 | 461.6 | 11.3 |
| 256 | 17.5 | 230.8 | 6.3 |
| 128 | 13.5 | 115.4 | 4.8 |
| 64 | 11 | 57.7 | 3.9 |
| 32 | 9.5 | 28.9 | 3.4 |
| 16 | 8.5 | 14.4 | 3.1 |
| 512 | 31.5 | 461.6 | 11.3 |
| | $C_w$ = 0.428 | | |
| 512 | 39 | 461.6 | 14.0 |
| 256 | 25 | 230.8 | 8.9 |
| 128 | 19.5 | 115.4 | 7.0 |
| 64 | 16.5 | 57.7 | 5.9 |
| 32 | 14 | 28.9 | 5.0 |
| 16 | 11.5 | 14.4 | 4.1 |
| | $C_w$ = 0.468 | | |
| 512 | 53 | 461.6 | 19.0 |
| 256 | 40 | 230.8 | 14.4 |
| 128 | 32.5 | 115.4 | 11.7 |
| 64 | 27 | 57.7 | 9.7 |
| 32 | 22 | 28.9 | 7.9 |
| 512 | 53 | 461.6 | 19.0 |
| 256 | 40.5 | 230.8 | 14.5 |
| 128 | 32 | 115.4 | 11.4 |
| | $C_w$ = 0.509 | | |
| 512 | 98 | 461.6 | 35.1 |
| 256 | 76 | 230.8 | 27.2 |
| 128 | 60 | 115.4 | 21.5 |